Technical Report Documentation Page

1. Report No. UMTA-MA-06-0100-81-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Pilot Study for Definition of Track Component Load Environments		5. Report Date February 1981
		6. Performing Organization Code DTS-741
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9. Performing Organization Name and Address 1Kaman AviDyne, 83 Second Ave., Burlington MA* 2 Kaman Sciences Corporation, Colorado Springs CO(Subcon) 3Thomas K. Dyer, Inc. Lexington MA (Subcontractor)		10. Work Unit No. (TRAIS) UM148/R1711
		11. Contract or Grant No. DOT-TSC-1605
12. Sponsoring Agency Name and Address U.S. Department of Transportation Urban Mass Transportation Administration Office of Technology Development and Deployment Washington DC 20590		13. Type of Report and Period Covered Final Report October 1978-May 1980
		14. Sponsoring Agency Code UTD-30

15. Supplementary Notes

*Under contract to: U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge MA 02142

16. Abstract

This report describes the results of an experimental and analytical effort to define the vehicle induced load environment in an at-grade, concrete tie/ballast transit track structure. The experiment was performed on the UMTA transit track oval at TTC in Pueblo, Colorado in order to establish an initial data baseline which could be extended to include data from tests conducted on various transit track structural systems. Standard experimental techniques generally were used to measure the pressures, strains and applied wheel/rail loads in the various track structure components; however, innovations were effectively introduced for measuring pressures on the bottom of the concrete tie and in the ballast. Track design methods and analytical computer techniques for predicting the load environment in the various track components were evaluated through comparisons with the experimental data. Design conservatism in the tie/ballast transit track systems was evaluated from the aspect of stress criteria versus other design factors based on experience and initial capital costs versus maintenance costs for transit systems. It was indicated from these tests, performed on a well constructed and maintained track structure, that there exists significant conservatism based on stress criteria, but the transit industry believes that the savings on construction costs for a more optimal stress design would be overshadowed by anticipated increases in maintenance costs. It is indicated by the results of this effort that many of the design stress methods currently being used should be improved, especially in the prediction of the load environment in the ballast and subgrade. It is anticipated that the experience gained in this pilot study can be applied in defining the load environment for other transit track configurations.

17. Key Words Load Environment, Track Costs, Track Components, Transit Track Design, Track Instrumentation, Transit Track Testing		18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 218	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This effort was performed for the Transportation System Center (TSC), Cambridge, Massachusetts under Contract DOT-TSC-1605 by Kaman AviDyne, Burlington, Massachusetts. This work was sponsored by the Office of Rail and Construction Technology, Office of Technology Development and Deployment, Urban Mass Transportation Administration (UMTA), Washington, D.C. and performed through UMTA's Urban Rail Construction Technology Program under the direction of Gilbert Butler. John Putukian was the technical monitor for the Transportation Systems Center and Lawrence J. Mente was program manager of this effort for Kaman AviDyne.

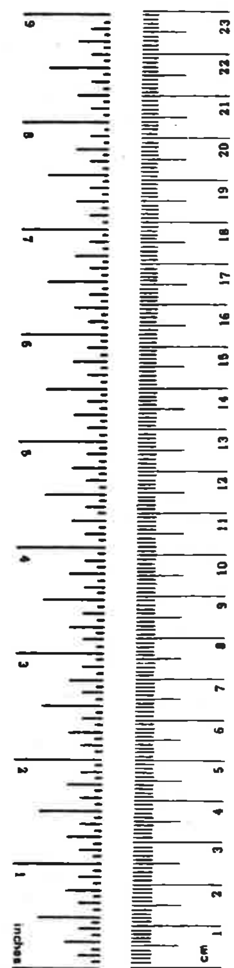
The work reported herein is the result of the coordinated participation of three groups, namely, Kaman AviDyne, Burlington, Mass., and subcontractors Kaman Sciences Corporation, Colorado Springs, Colorado and Thomas K. Dyer, Inc., Lexington, Mass. In this report Kaman AviDyne generated Sections 1, 2, 5.2, 4, and 7, Kaman Sciences Corporation generated Section 3 and Appendices B through E, and T.K. Dyer, Inc. generated Sections 5.1 and 6 and Appendices A and F.

The authors wish to acknowledge the cooperation and valuable guidance of Robert Brush, TSC Representative at TTC, and Gunars Spons, Director, UMTA Programs at TTC in the performance of the experiment at the UMTA transit test track site in Pueblo, Colorado. Robert Schnepp and John Angelbeck of Kaman Sciences and Robert Sheldon and Robert Swearingen, Jr. of Dynalectron Corporation also deserve recognition for their participation in the experimental program at TTC. Hon-Yim Ko and Myoung Mo Kim are also acknowledged for the soil testing performed at the University of Colorado. Finally, the authors wish to acknowledge appreciation for the reviewing of this program by the American Public Transit Association (APTA), Track Construction and Maintenance Subcommittee.

METRIC CONVERSION FACTORS

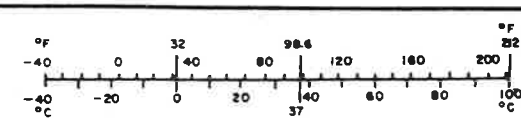
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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LIST OF ABBREVIATIONS

AAR	American Association of Railroads
APTA	American Public Transit Association
AREA	American Railway Engineering Association
cwr	continuous welded rail
FAST	Facility for Accelerated Service Testing
kips	thousands pounds (force)
KSC	Kaman Sciences Corporation
MBTA	Massachusetts Bay Transit Authority
mph	miles per hour
NYCTA	New York City Transit Authority
TSC	Transportation Systems Center, Cambridge MA
TTC	Transportation Test Center, Pueblo CO
TTT	Transit Test Track, at TTC
UMTA	Urban Mass Transportation Administration, Washington DC

1. INTRODUCTION

The determination of vehicle induced forces on various transit track configurations should enhance the understanding of the load environment within each component of the track system and aid in the ongoing effort to improve design methods and system maintainability. Currently, the design standards are governed by the materials presently used in the track system, by the history of construction methods and practices used in the industry and by the general experience of acceptable limits for safety, ride quality, reliability and, probably most important, economics. Track design practices may be categorized as approaches primarily relying on the designer's experiences and on some handbook specifications and/or recommendations. The design criteria used are related to the strength of individual components, material availability and cost considerations.

Operational rail systems are expected to achieve certain performance levels based upon safety, ride quality, noise and ground vibration and maintainability (and thus also long term costs). Many design procedures do not consider performance aspects per se; but they do try to meet the strength criteria which are indirectly related to performance. A reliance upon basic strength calculations tempered with a tremendous amount of past experience tends to be the design method used by present day designers to achieve the required track system performance criteria.

Current transit design practices are spinoffs from established railroad track technology and, therefore, may result in conservatism in track system design for the lighter transit vehicles. There are major considerations that should be taken into account when evaluating transit versus railroad track systems. Railroad tracks are almost all at-grade tie-ballast construction, while transit tracks have different segments: at-grade, elevated and underground, which can involve tie-ballast or concrete slab construction with direct fixation fasteners. Ballasted track construction for both railroad and transit systems use either wood or prestressed concrete ties, but in transit track systems, curves have shorter radii of curvature, maintenance is constrained due to short operational headways and short periods of night closings, and operation is within the confines of densely populated areas. If improved and economical transit track systems are to be achieved for urban areas it is necessary that the transit track design community be provided with a better understanding of the load environment in all of their transit track components. This better defined load environment should also result in improved design tools for the designers, and may influence general maintenance procedures.

To improve the design techniques, it is necessary to evaluate load environment predictions obtained with the current design methodologies for the various track components. This can be accomplished by comparing the load environment obtained from current practices with experimental data from well controlled field tests. If it turns out from these assessments that the presently used load prediction techniques for transit track design are unsatisfactory in certain aspects, then the prediction and utilization techniques should be improved. Such improvements must be in "practical terms" and economically justifiable if they are to be understood, accepted and used by the designers.

This pilot study is an initial effort to define the track component load environment for a selected transit track system. Thus, the limited objective of this initial program is to define the load environment in a transit track system of at-grade concrete tie-ballast type of construction from vehicle induced forces. The experiment for determining the load environment in the ties, fasteners and ballast/subgrade components of this track configuration provides data for comparisons with the analytical tools currently being used in the industry. The current track design methods are to be evaluated and the degree of conservatism existing in current practice is to be identified for the tested transit track configuration.

The UMTA transit test track (TTT) at the Transportation Test Center (TTC) at Pueblo, Colorado was selected by DOT/TSC as the test site to perform the experimental determination of the vehicle induced forces. It was felt that the initial test effort should be at the controlled environment provided by this UMTA facility. A test plan for measurement of track component loads using current state-of-the-art instrumentation techniques was developed and implemented at tangent and curved sites selected along the TTT. In this effort the available computer analyses and design methods used to predict the load environment for tie-ballast track configurations are reviewed and applied to the selected track configuration at TTC. The uncertainties existing in the load prediction techniques are evaluated and compared with experimental results. The degree of conservatism implied by the specific load environment obtained in this pilot study is assessed considering the initial construction costs and the eventual maintenance cost for a transit track system.

A program summary is given in Section 2 which gives the reader an overall view of what was accomplished during the study. The description of the load environment experiment conducted at TTC is given in Section 3. In Section 4 the test results are presented and evaluated, and load environment comparisons with analysis and design values are made. In Section 5 transit track design techniques are presented and current numerical computer models of the track structure are generated and discussed. An assessment of the degree of conservatism in track design is made in Section 6. The conclusions and recommendations are presented in Section 7 and various appendices which support the main sections of the report are presented after this section.

2. PROGRAM SUMMARY

2.1 BACKGROUND

This pilot study represents the start of a program to examine the vehicle induced force environment on various transit track systems. This initial effort is directed towards an at-grade tie-ballast transit track configuration selected on the UMTA transit test track at TTC Pueblo, Colorado. The purpose of the study is to provide data defining the load environments in the ties, fasteners and ballast/subgrade components of the transit track structure selected. These data are then used to compare with results from existing computer code models and design methods. Based on the results from the track configuration tested, an assessment of the degree of conservatism in present transit designs is made from the structural aspect and a first cut evaluation of initial cost versus maintenance costs is made relative to this assessment.

The UMTA transit test track at Pueblo is illustrated in Figure 2.1. The test track is divided into six sections, and each section is of a different type of track construction as indicated in Figure 2.1. A tangent and a curved site on the concrete tie with welded rail section (Section IV) were selected for track structure measurement locations. The locations of the old existing wayside test stations are designated as TTC-4A (near station 365) and TTC-4B (near station 428). New instrumented stations were established very near the existing stations and are designated as KSC-1 and KSC-2. The new instrumented stations were the primary data acquisition source while the old existing stations (installed in 1971) provided very little useful data due to degradation of transducers and the lack of recorded calibration information. This track section consists of 119 lb welded rail with Gerwick RT-7 Mark 38 pre-stressed concrete ties spaced at 30 inches on tangent and 27 inches on curved track. The rails are attached to the concrete ties by the Rails Company "Flexiclip" fasteners. The depth of the ballast is 12 inches and consists of crushed stone AREA No. 4 gradation. The subballast is 6 inches of ungraded stone. The subgrade in the region of the test stations can be categorized generally as silty sand.

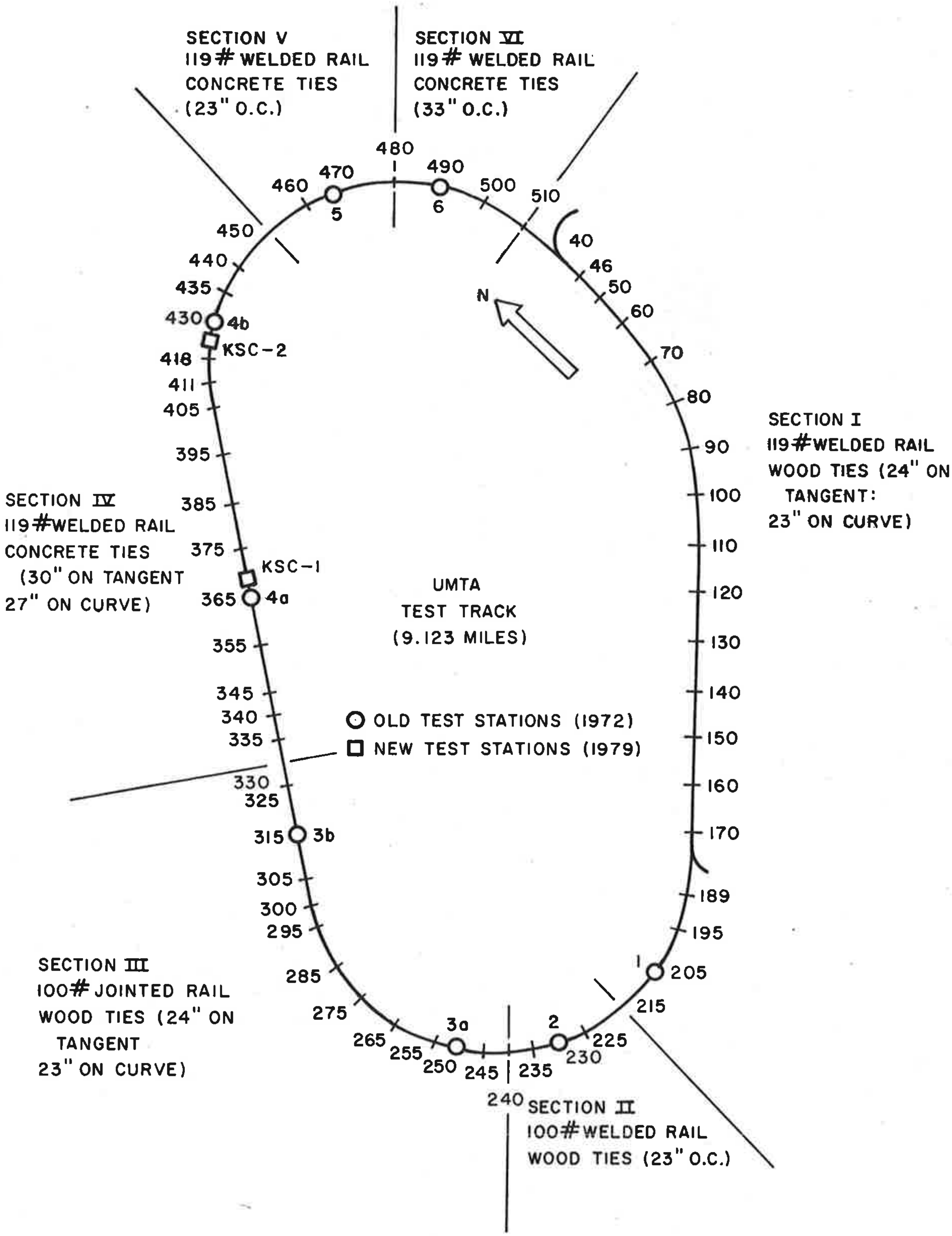


FIGURE 2.1. UMTA TRANSIT TRACK TEST SITE

The types of measurements made at these wayside test stations include wheel/rail loads, bending strains on concrete ties, strains in fastener clips, and pressure and strains in roadbed structure (ballast, subballast and subgrade). Figure 2.2 shows the cross section of the track structure and the general instrumentation locations at the KSC test stations. In addition to this instrumentation profile at KSC-1 and KSC-2, 12 other ties at each site were strain gaged for bending at three positions on the tie. At the tangent site 10 additional wheel/rail load measurement locations were instrumented on the outside rail. They were spaced so as to record loads for the entire circumference of the transit vehicle wheel. These measurements were made during the passage of transit vehicles at prescribed speeds. In particular, six test-vehicle configurations were used, namely: two NYCTA R-42 cars in tandem at two weight conditions (crush and empty) and at two speeds (30 and 50 mph), and two MBTA cars (Blue line) at crush weight and two speeds (30 and 50 mph).

2.2 RESULTS AND CONCLUSIONS

The experimental data is examined by track system component type: wheel to rail vertical and lateral load transfer, tie bending moments, ballast and subgrade pressure and strain distribution, rail-tie fastener strains, and soil material definition. The experimental data is compared to itself for different vehicle configurations, compared to other known applicable experimental data and used as a basis for an analytical correlation study. In parallel with this experimental and analytical study of a transit track load environment, the cost of at-grade transit track construction is parametrically examined by component cost and by anticipated effects on maintenance cost.

The wheel to rail loads data is compiled from both the loads measured during the gathering of tie and roadbed data with variable vehicle configurations at the tangent and curve sites and from the specific wheel to rail loads study conducted at the tangent site with a crush loaded R-42 vehicle traveling at either thirty or fifty miles per hour passing through a special instrumentation layout. The specific wheel to rail

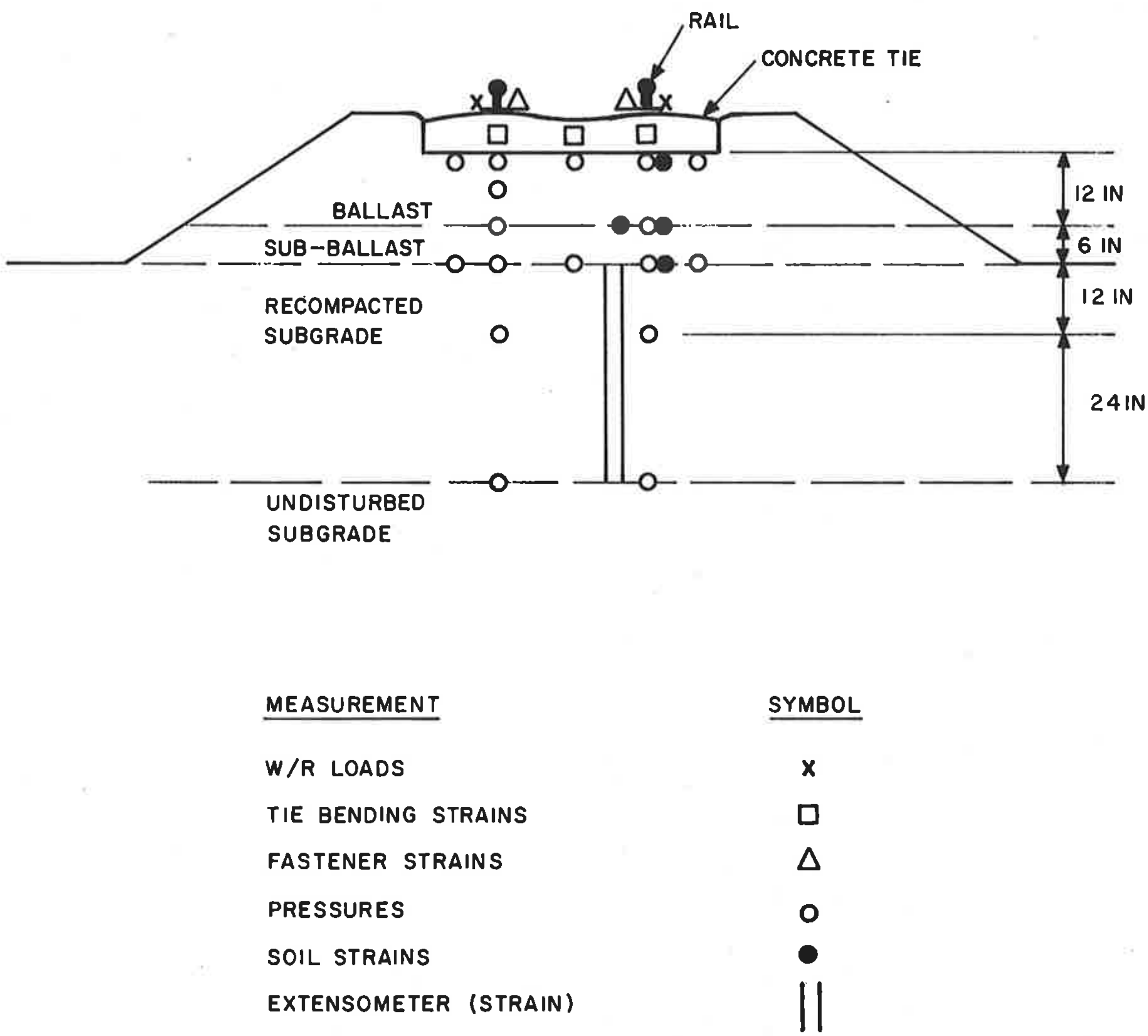


FIGURE 2.2. INSTRUMENTATION LOCATIONS AT KSC TEST STATIONS

loads study conducted at the tangent site with the crush loaded R-42 vehicle indicates no statistically significant differences among vertical or lateral applied wheel laods at either thirty or fifty miles per hour. One of the parameters that affects the magnitude of the load transferred from the wheel to the track structure is the wheel flats. This study includes the effects of wheel flats but the track geometry is without any measured perturbations. The additional wheel to rail loads data gathered at both the curve and tangent sites for the six test-vehicle configurations show negligible differences in applied vertical load between the tangent and the curve (3820 foot radius, 1°30') and indicate that the lateral loads are two to three times larger at the curve for each vehicle configuration. The statistical study at the tangent site indicates a design laod factor defined as the load that is exceeded only five percent of the time with a ninety-five percent confidence level. For the tangent site and the crush loaded R-42 at either velocity these design loads are 18 kips vertical and 4 kips lateral.

At each site (tangent and curve) thirteen ties were instrumented for tie bending moment measurements. For the crush loaded R-42 vehicle all the ties responded similarly, there were no unbalanced bending moments at the curve and the maximum bending moments measured were approximately one-half the design value. The present design formulations, both numerical and analytical, provide excellent correlations between the predicted and the measured bending moments.

The ballast and subgrade pressures were measured at sixteen locations at both the tangent and curve sites. Differences in pressures measured under the inner or outer rail seat at either site appear to be due more to roadbed construction and ballast tamping than to vehicle configuration or track curvature. The present eighteen inch ballast and subballast depth provides a reasonably even pressure distribution at the top of the subgrade, regardless of the pressure distribution measured at the tie/ballast interface. The maximum pressures measured at the top of the subgrade or the tie/ballast interface are all below design standards by at least a factor of three, and all of the pressures measured in the recompacted subgrade are negligible and should not influence the untreated subgrade. The presently used design formulae could not predict accurately the pressures at the top of the subgrade and there was a 100 percent scatter in predictions among AREA recommended design formulas. The numerical predictions provided by the ILLITRACK and MULTA computer codes showed fair to reasonable correlation with the experimental data, once the appropriate material description for the ballast and subgrade was determined.

The roadbed strains and deflections were all small and measurably elastic. These deformations compared reasonably well with measurements conducted at the nearby FAST facility - with similiar vehicle truck loads and similar roadbed geometry. The main usefulness of the strain and deflection instrumentation is for the long term examination of the settling and "aging" of the track roadbed. This information can then be used to follow the history of track component load levels.

Four fasteners were measured for dynamic strain levels at each site. This data shows that the maximum stress levels experienced by the fasteners are below the yield level by an approximate factor of two. The measured dynamic stress increment placed on the fasteners during vehicle passage was determined to be sufficiently small that the fastener should be able to complete its design life without a bending fatigue failure. This fastener study did not examine the tie down bolts or the bolt to concrete tie fixture, and the study did not include track perturbations which would lead to significantly different fastener stress levels.

The subgrade soil was sampled at the tangent site, and six soil samples representing three soil depths were triaxially tested. Six different stress paths were used in the triaxial tests to examine the effects stress paths (especially "dynamic" stress paths induced by a rolling wheel) have on the soil material properties. More samples and more varied stress paths are needed to provide statistically significant results, but these preliminary tests indicate some response differences among the various stress paths. All the stress path data from the two samples representing the top of the subgrade soil were used to determine the material constants to be used in the ILLITRACK and MULTA numerical analyses. These material constants appeared to be a reasonable representation of the soil and showed good correlation with material constants determined at the nearby FAST facility.

A parametric study was carried out examining the relative effects that changes in rail size, tie size, tie spacing, and ballast depth have upon the initial construction cost of a transit track system. The loads study (experimental and analytical) showed that, based upon stress criteria, the applied industrial design standards had overdesigned the UMTA transit test track. Indeed, thirty-three inch tie spacing is employed in the adjoining curve (Section VI) of the TTT (see Figure 2.1) which exceeds design practice by six inches; there have been no unusual maintenance problems here during the seven year existence. The parametric study indicates that significant construction cost savings can be made by varying the appropriate component designs. It was found that varying tie size and spacing and varying ballast depth have the most significant effect upon the construction cost, and based upon design stress criteria these three variables could be changed without exceeding design stress maximums. However, other design criteria have not been accounted for totally nor have the effects upon maintenance costs been fully evaluated. It is concluded that life cycle loads and therefore maintenance costs must be examined carefully before design procedures could be altered.

Overall, a reasonably complete description of the track component single cycle load environment has been determined and found to be conservative. The design practices are enumerated, and examples carried out, and comparisons are made with newly developed numerical computer codes. A parametric study of the effect of individual component design upon construction costs is examined, and potential construction cost savings are indicated, but the effects upon maintenance costs are indeterminable from this pilot study.

3. TRANSIT TRACK LOAD ENVIRONMENT EXPERIMENT

A primary task of this program effort was to determine the load environment of a transit track system by experimental measurements at a representative transit site. An extensive set of measurements was therefore made in transit track ties, ballast, subballast and subgrade in order to form a data base for use in evaluating current transit design methods and current numerical analysis techniques.

3.1 SITE SELECTION

TSC determined that the UMTA transit test track (TTT) at the TTC facility in Pueblo, Colorado, would provide a representative sample of well built transit track designed by the current state-of-the-art techniques. The TTT shown in Figure 2.1 is configured with several combinations of ties, rail and tie spacing. TSC selected the concrete ties and continuously welded rail section of the test loop for the experiment, since this section is representative of new at-grade transit track construction. Two sites along the TTT were chosen for instrumentation, and both sites are located in close proximity to existing instruments that were installed during the construction of the TTT. There is a tangent and a curved site with identical rail, ties, fasteners, ballast, subballast and subgrade materials leaving only the tie spacing and track curvature as variables. The curved site has a 1.5 degree curvature (radius equal to 3820 feet) which is substantially more gradual than typical transit curves but is the maximum curvature existing along the TTT. The test site includes a 0.69 percent grade clockwise from the tangent site to the curved site. The tangent site is designated KSC-1 and is located near track station 365 and approximately twenty eight feet from instrument site TTC-4A. The curved site is designated KSC-2 and is located near track station 428 and approximately twenty seven feet from instrument site TTC-4B.

3.2 TRACK MATERIALS

Both test locations are configured as follows:

Rail	119 lb Welded Rail
Tie	Gerwick RT-7 Mark 38 Prestressed Concrete Tie

Fastener	The Rail Co. "Flexiclip"
Tie Spacing	30 in. on tangent track
	27 in. on curved track
Ballast	12 in. of Crushed Stone AREA No. 4 Gradation
Subballast	6 in. of ungraded stone
Subgrade	Silty Sand

The subgrade consists of a thirty inch depth of recompacted soil above the undisturbed subgrade. The track materials and tie spacing are similiar to those used in present day construction of at-grade transit track.

3.3 REQUIRED MEASUREMENTS

The experimental task of this study was to determine the loads induced in the transit track system from the rails down into the undisturbed subgrade by the passage of transit vehicles. There have been no previous comprehensive measurements of this type performed on transit track systems. The types of measurements of primary interest to be obtained are as follows:

a) wheel-to-rail vertical and lateral loads
b) rail seat loads
c) tie bending moments
d) tie-ballast pressure
e) ballast-subballast pressure
f) pressure distribution in subballast
g) tie settlement
h) ballast and subgrade strains

3.4 EXISTING INSTRUMENTATION

The selection of the locations for instrumentation sites KSC-1 and KSC-2 included the desire of close proximity to existing instrumentation sites as mentioned in Section 3.1 and illustrated in Figure 2.1. Instrumentation sites TTC-4A and TTC-4B were installed during the construction of the TTT in 1972. The instrumentation consisted mainly of Bison soil strain measurement systems and soil pressure gages (Gentran and Carlson types). All of this instrumentation was installed in the track ballast as shown in Figure 3.1, and there were no instruments placed into the recompacted subgrade. Upon examination of these previously installed instruments it became apparent that many transducers had degraded, and calibrations were no longer available for others. Very limited data were obtained from those transducers that were still operating for comparison with the newly-installed transducers.

3.5 TRANSDUCER SELECTION

Transducer selections for the experimental activities were based on one or more of the following considerations: cost, availability, commonality with existing TTT transducers and/or contractual direction. The following paragraphs describe selection of the various transducers and transducer applications employed in instrumentation of the curved and tangent test areas of the TTT.

3.5.1 Crosstie Strain Gages

KSC consulted with personnel of the Waterways Experiment Station (WES), Corps of Engineers in Vicksburg, Mississippi, regarding strain gage instrumentation and calibration of concrete crossties. The WES had previously been involved in similar efforts with concrete crossties utilized in the TTC Facility for Accelerated Service Testing (FAST) track, and this experience was deemed directly applicable. Recommendations received and utilized included use of full-bridge strain gage circuits for maximum signal output, isolation of the inactive strain gages from rail seat stress gradients, and methods of detection and filling of subsurface voids in the strain gage areas. In addition, the WES load calibration testing experience to determine rail seat strains was considered by KSC in specification of laboratory test procedures.

3.5.2 Rail Clip Strain Gages

Strain gages were selected as the method for assessment of the stress condition in the rail clips in view of time and cost constraints. A small gage length was selected because of the varying stress field in

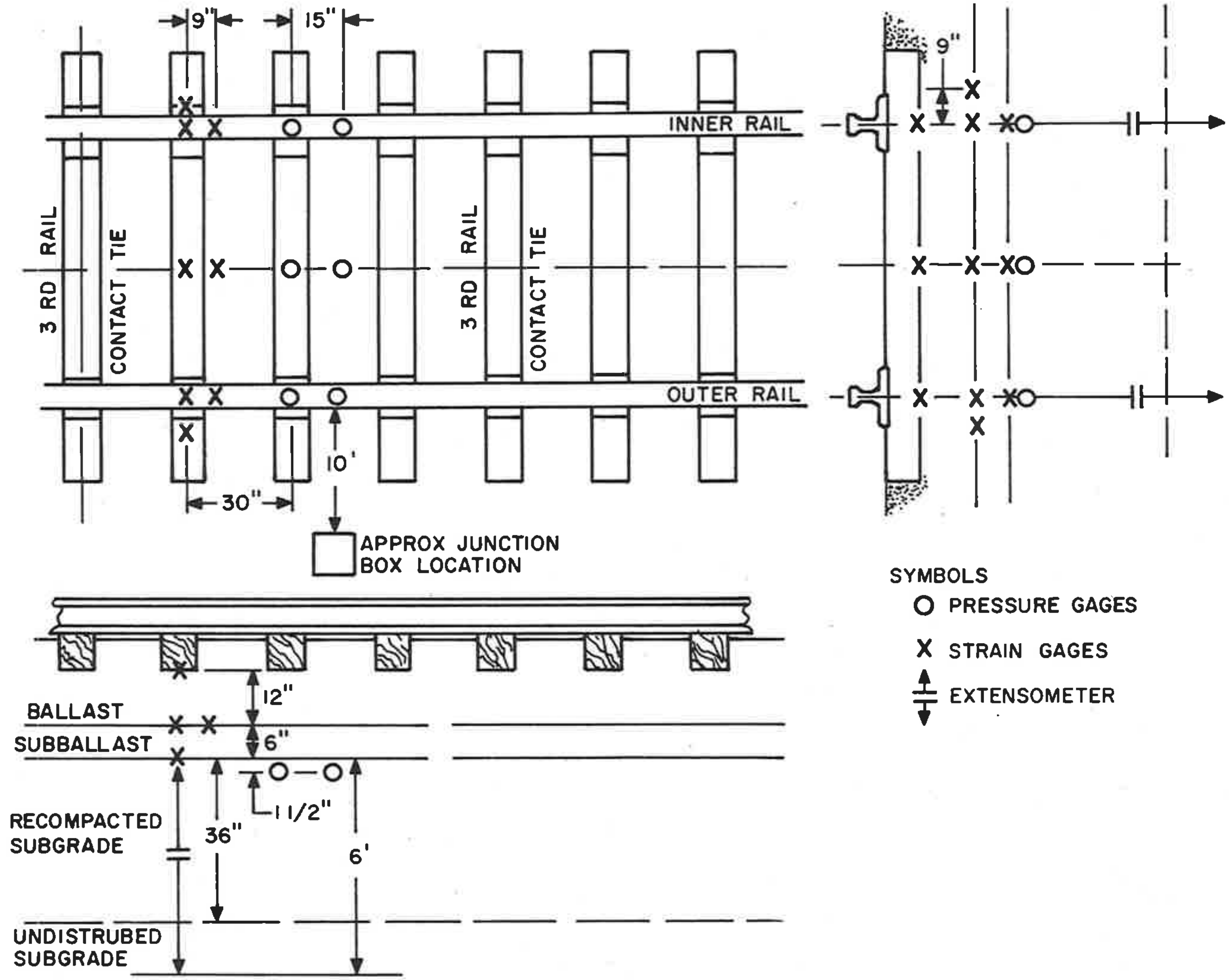


FIGURE 3.1. INSTRUMENTATION LOCATIONS AT TTC-4A & B TEST STATIONS

the only accessible gaging surface. These strain gages provide an indication of the load environment of the fastener clips and their susceptibility to fatigue. The use of these strain gages for measuring the rail seat loading was also considered (see Section 3.5.7.).

3.5.3 Lateral/Vertical Wheel Rail Load Circuits

KSC opted to employ the web and base chevron strain gage circuits for measurement of vertical and lateral wheel-rail loads. This method is the generally accepted one, and the TTC had available locating fixtures and templates to assure accurate gage placements. Hitec weldable strain gages were selected because of favorable TTC experience in this application. The lateral circuits were load calibrated while subjected to constant vertical loads encompassing the expected range thereof to account for the known effects of vertical load on lateral circuit sensitivity.

3.5.4 Sensotec Soil Pressure Gages

Several alternative soil pressure transducers were considered for use in this effort. The selection of Sensotec gages was made primarily on availability and cost. These gages were implanted directly in the soil, encapsulated between bearing plates in both the soil and in the ballast, and imbedded in crosstie bottom surfaces. Encapsulated and imbedded Sensotec gages were subjected to laboratory load calibration to determine output characteristics when loaded by planar surfaces.

3.5.5 Bison Soil Strain Measurement System

Bison instrumentation and transducers were employed to measure roadbed strains and deflections in the TTT at Stations 4A and 4B. The TTC had available the calibration fixture and the electonics unique to these transducers. KSC was aware of the cumbersome aspects of these gages for dynamic response applications and the effects of large bodies of metal, such as a transit vehicle, upon both the zero reference and sensitivity. Because of the inherent limitations, only one Bison array was employed to measure ballast strains at each test area.

3.5.6 Soil Extensometer

Carlson stress meters were among the transducers originally installed in the TTT roadbed at Stations 4A and 4B, while soil extensometers there operated on the Bison principle. In view of the known limitations of Bison measurement systems for this application, KSC opted for extensometers employing Carlson joint meters. The company responsible for fabrication and installation of the Carlson stress meters at Stations 4A and 4B was selected to design and fabricate two Carlson joint meter extensometers for installation at Stations KSC-1 and KSC-2.

3.5.7 Rail Seat Loads

As pointed out in Section 3.5.2, strain gages were installed on the fastener clips in order to measure the stress in the fasteners. This method was discovered to be unreliable for the alternate use of accurately determining the rail seat loads. However, other methods that have been previously used in the measurement of rail seat loads, such as load cell transducers placed under the rail, are known to alter the normal response of the rail-tie system to the induced vehicle load. Use of transducers such as load washers beneath the attachment bolt heads or instrumented bolts was rejected because of the variable surface of the rail clip interface and the eccentric loading that such transducers would experience. Therefore, these methods were not used to measure rail seat load, and this load detail was left undetermined in this experimental effort.

3.5.8 Miscellaneous Transducers

The remaining transducers including the moisture density meter, thermocouple arrays, and optical speed indicator were TTC equipment operated by the TTC O&M contractor.

3.6 PREPARATION/CALIBRATION ACTIVITIES

Various preparatory activities preceded excavation and installation of transducers and instrumented track structure components in the Transit Test Track. These included instrumentation and laboratory load calibration of concrete crossties, encapsulation and load calibration of ballast Sensotec soil pressure gages, installation of strain gages on rail clips, and evaluation of and compensation for the effects of large metallic objects on Bison soil strain coils. These activities are discussed in detail in the following paragraphs.

3.6.1 Concrete Crossties

Four used Gerwick RT-7, Mark 38 crossties identical to those existing at the two test areas were obtained from TTC inventory for special instrumentation and laboratory load calibration prior to installation in the Transit Test Track for testing. Instrumentation consisted of five full bridge strain gage circuits installed on each crosstie and five Sensotec soil pressure gages interfacing with steel ballast bearing plates recessed flush into the bottom surfaces of two of these crossties as shown in Figures 3.2 and 3.3.

A fixture for locating strain gage positions at the rail seat and midspan areas was designed and fabricated for use on this program. As shown in place in Figures 3.4 and 3.5, this fixture indexed off the gage side rail clips and fasteners and permitted accurate and repeatable marking of the strain gage locations. By measuring strains at the same points on all crossties, the need for performing laboratory load calibrations on the eleven crossties strain gaged in situ at each test area was partially obviated.

Each four arm strain gage circuit was comprised on one BLH FAE2-300-35-S6L two-arm active gage (3-inch length) and one BLH FAE2-25-35-S6L two-arm inactive gage (1/4-inch length). The 3-inch gage length was selected to average out effects of internal aggregates on the surface strain. Availability considerations precluded use of a longer gage, such as 5-inches, which would have been preferable for strain averaging.

Surface preparation of the concrete for installation of the active gages consisted of light tapping to reveal any internal voids followed by surface grinding. Small voids and imperfactions were filled by successive applications of epoxy followed by light sanding. The final strain gage application surface was smooth and flat and was essentially the concrete surface with all voids filled. Gages were applied using manufacturer's specifications and recommendations.

Each inactive gage was bonded to a small piece of phenolic which in turn was cemented with RTV to the crosstie adjacent to the active gage. The phenolic was selected to provide approximately the same

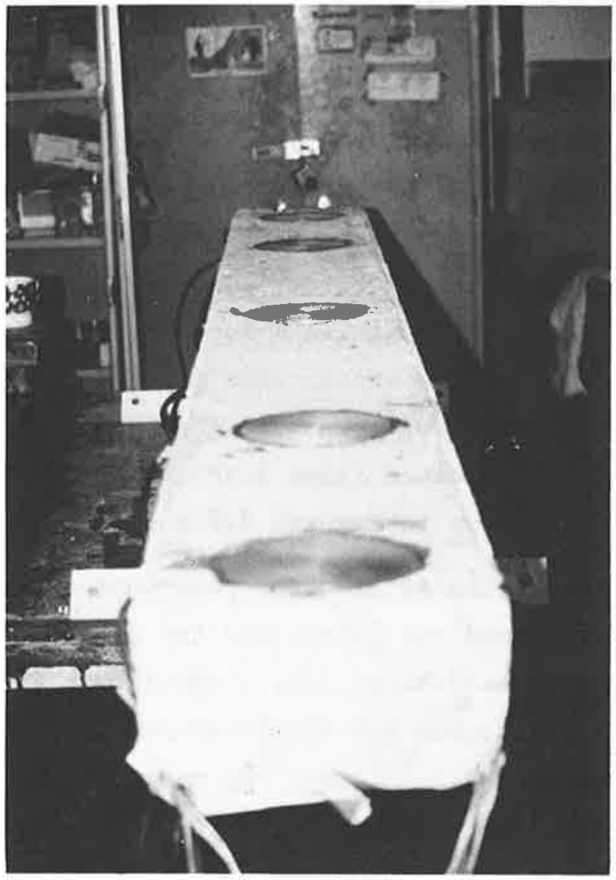


FIGURE 3.2. SOIL PRESSURE GAGES AND BEARING PLATES INSTALLED IN CROSSTIE BOTTOM SURFACE

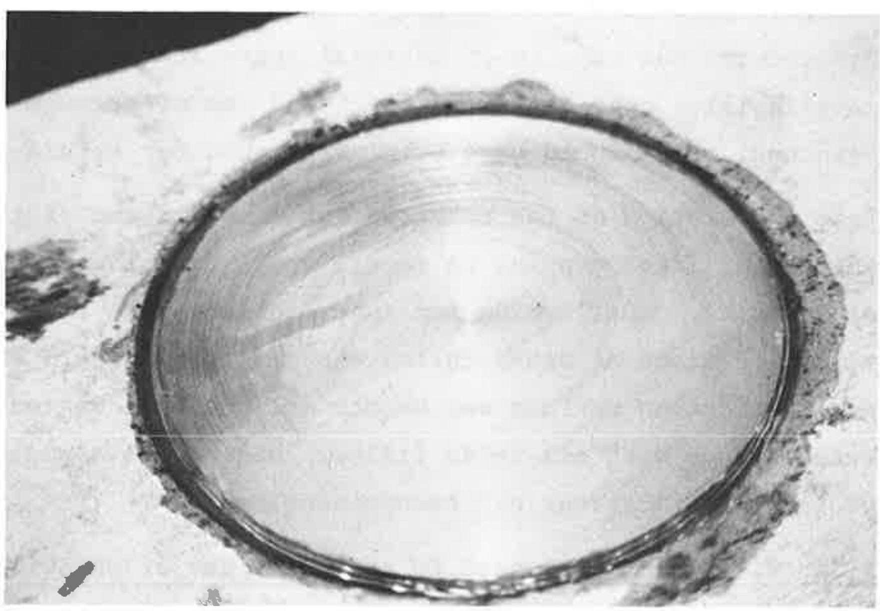


FIGURE 3.3. BEARING PLATE INSTALLED FLUSH WITH CROSSTIE BOTTOM SURFACE

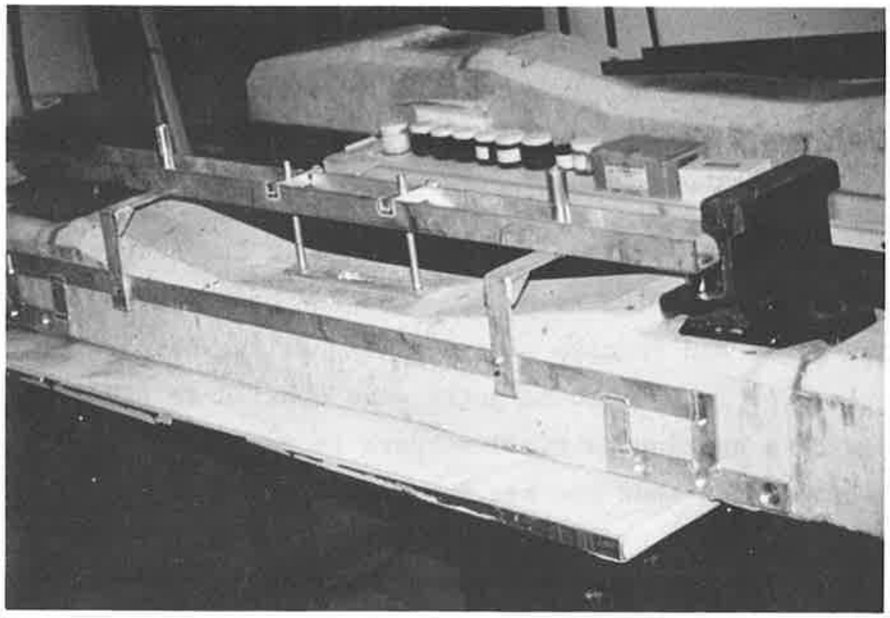


FIGURE 3.4. STRAIN GAGE LOCATING FIXTURE POSITIONED ON CONCRETE CROSSTIE

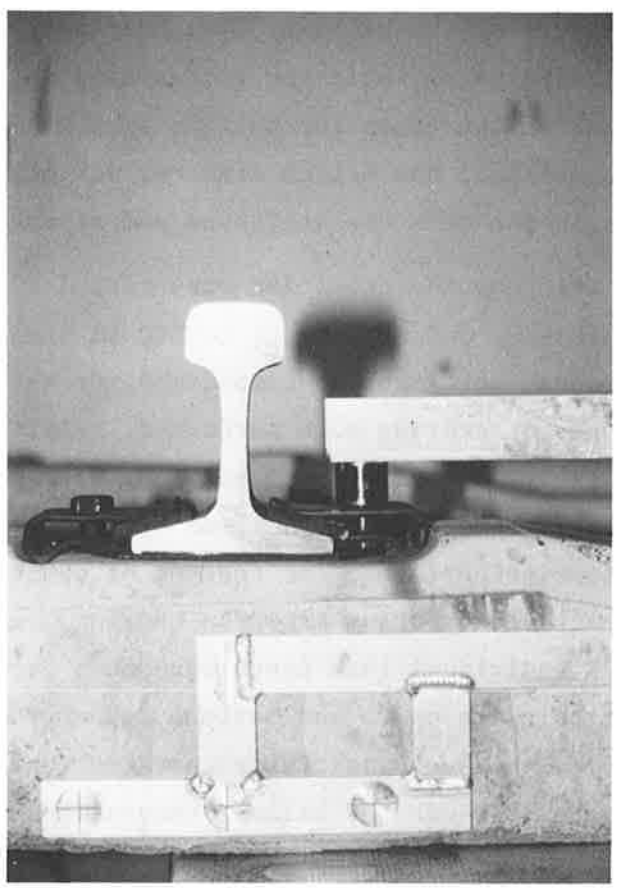


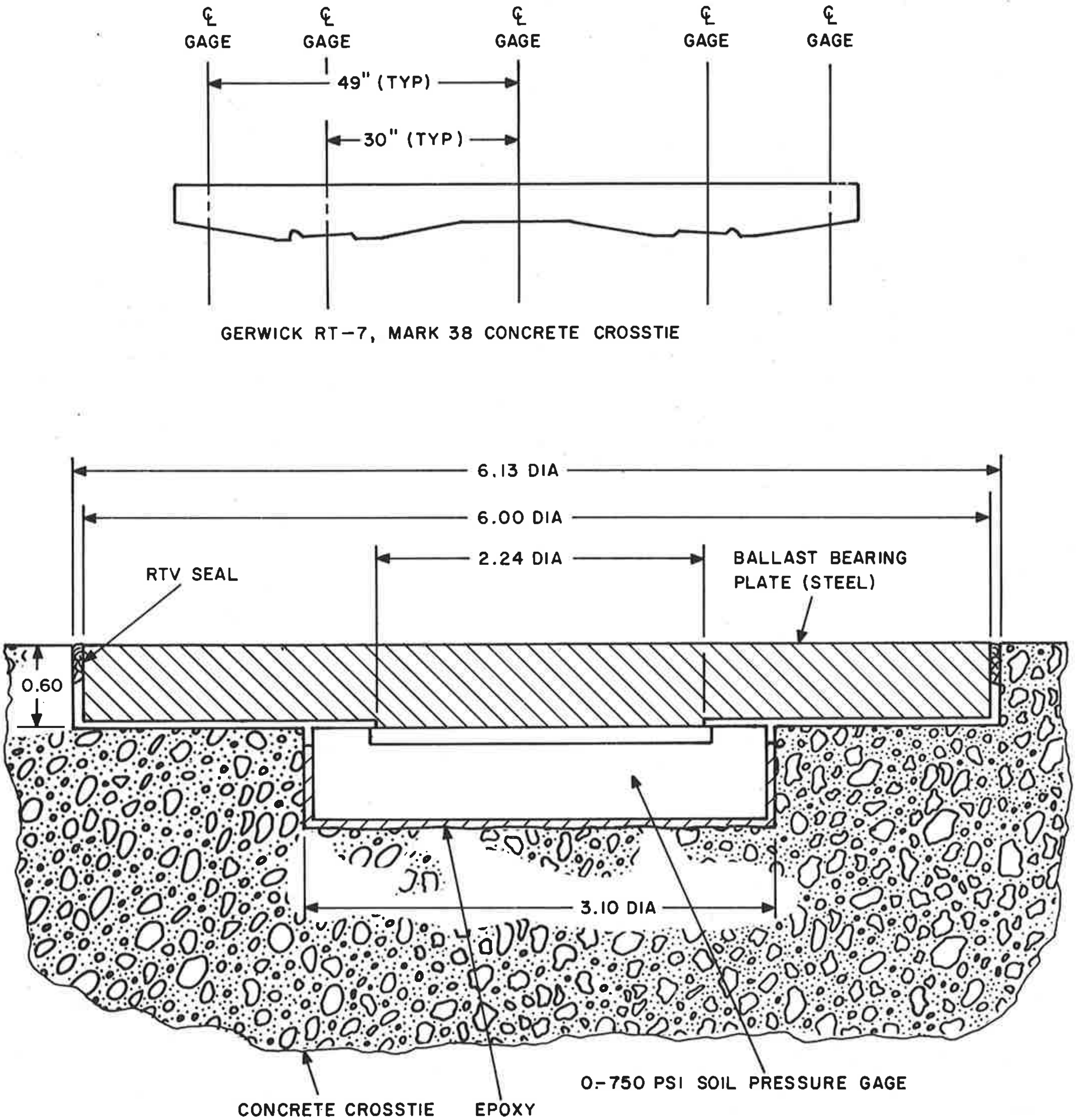
FIGURE 3.5. RAIL SEAT MARKING TEMPLATE DETAILS, STRAIN GAGE LOCATING FIXTURE

thermal expansion characteristics as the concrete, although no long-term temperature compensation was required for this effort. The RTV provided isolation from strains induced in the concrete by transit vehicle passage.

Five two-step recesses were machined in the bottom surfaces of two of these used crossties to accept Sensotec Model SA-E, 0-750 psi soil pressure gages and cadmium plated steel ballast bearing plates as shown in Figure 3.6. The Sensotec gages were epoxied in place to prevent motion and provide a continuous rigid support to the back surfaces. The gages were located such that the bearing plates could be set flush with the bottom surface of the crosstie and maintained in place by a bead of RTV around the circumference.

The function of the bearing plate was to distribute uniformly the point loadings from the underlying ballast to the strain gaged diaphragm of the Sensotec gage. These gages, which were designed for use in a fluid or fluid-like medium, would give meaningless readings or be damaged by direct contact with the ballast. The bearing plate diameter was limited by a desire to minimize the recess size in the crosstie. Ideally, a plate diameter of ten times the ballast size is needed to average the loading irregularities; the 6-inch diameter was selected to avoid significant changes in the crosstie stiffness and strength characteristics.

The four instrumented crossties were tested by Hauser Laboratories in Boulder, Colorado, under contract to KSC in accordance with the test plan and procedures set forth in Appendix B, Crosstie Load Calibration Tests. Two types of testing were performed. Positive moment rail seat bending and negative moment midspan bending tests were performed on each crosstie, utilizing the set-up specified by the American Railway Engineering Association (AREA) for testing of concrete crossties. From these tests, the strain versus crosstie bending moment relationships were obtained. Individual load tests were then performed on each of the imbedded Sensotec gages up to the maximum capacity of the gage to ascertain the load versus sensitivity characteristics of these transducers when loaded through the ballast bearing plates.



NOTE: ALL DIMENSIONS IN INCHES

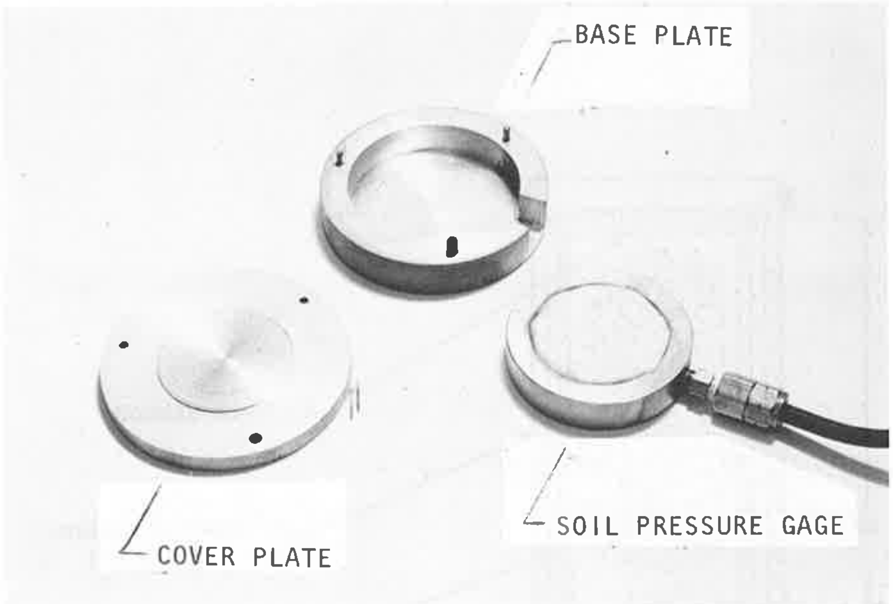
FIGURE 3.6. DETAILS OF SOIL PRESSURE GAGE INSTALLATION IN CONCRETE CROSSTIES

3.6.2 Encapsulated Pressure Gages

Sensotec Model SA-E soil pressure gages of various pressure ratings to be implanted in the ballast were first encapsulated between flat circular cadmium plated steel bearing plates as shown in Figure 3.7. These plates served the same function as the bearing plates imbedded in the crossties by distributing uniformly the point loadings from the surrounding ballast to the strain gaged diaphragm of the Sensotec gage. Bearing plate diameters were selected in accordance with the gage pressure rating and the expected ballast pressure levels. Four different diameters (4-, 5-, 7-, and 10-inch) were required because of the limited availability of gages having common pressure ratings. Before implantation, all encapsulated Sensotec gages were load tested to the maximum capacity of the gage to ascertain the load versus sensitivity characteristics when loaded through the encapsulation plates.

3.6.3 Soil Strain Gages

The Bison Model 4101A soil strain measurement system employing 4-inch sensors was employed to measure vertical and lateral ballast strain. In operation, receiver sensors are located at known distances from a common sender sensor. The separation of the sensors is related to the electromagnetic coupling between the receivers and senders. By means of an inductance bridge contained in the 4101A instrument package, an output voltage as a function of sensor displacement may be obtained since a change in spacing from the initial position produces a bridge unbalance. It was determined during preliminary calibrations that both the null indications and output sensitivities of the Bison system were affected by the presence of metallic bodies. To account for the effects induced by passage of the transit vehicles, a Bison field compensator was constructed as shown in Figure 3.8. This device consisted of one sender sensor situated between two receiver sensors with the same spacing as that employed in the active array. These sensors were supported in a plastic tube which isolates the array from ballast strain. The effects of transit vehicle passage can therefore be determined independently and used to correct the signals obtained from the active array.



"A" DIAMETER (INCHES)	GAGE PRESSURE RATINGS (PSI)
4.00	0–100
5.00	0–100 & 0-600
7.00	0–600
10.00	0–600

ALL DIMENSIONS IN INCHES

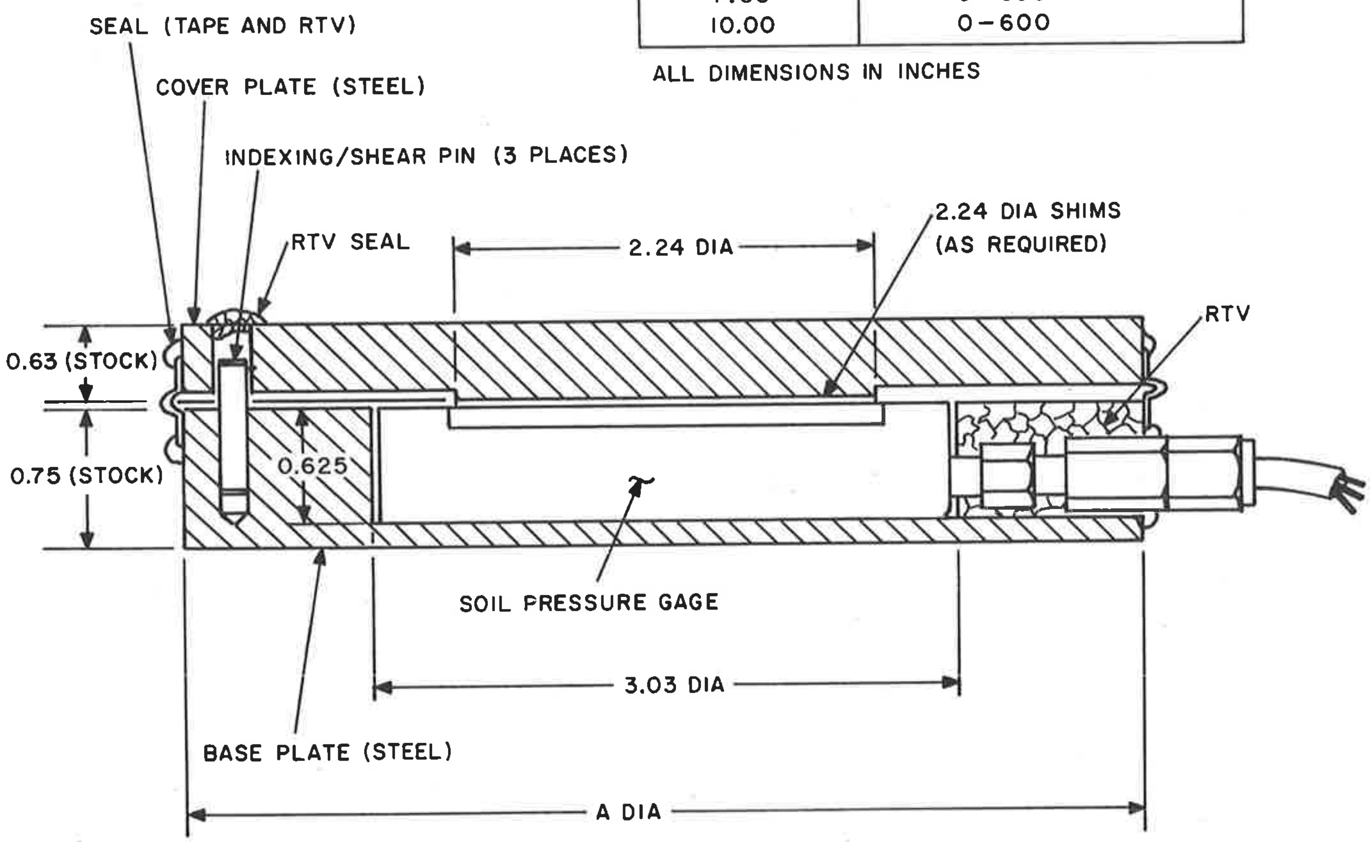


FIGURE 3.7. SOIL PRESSURE GAGE ENCAPSULATION DETAILS

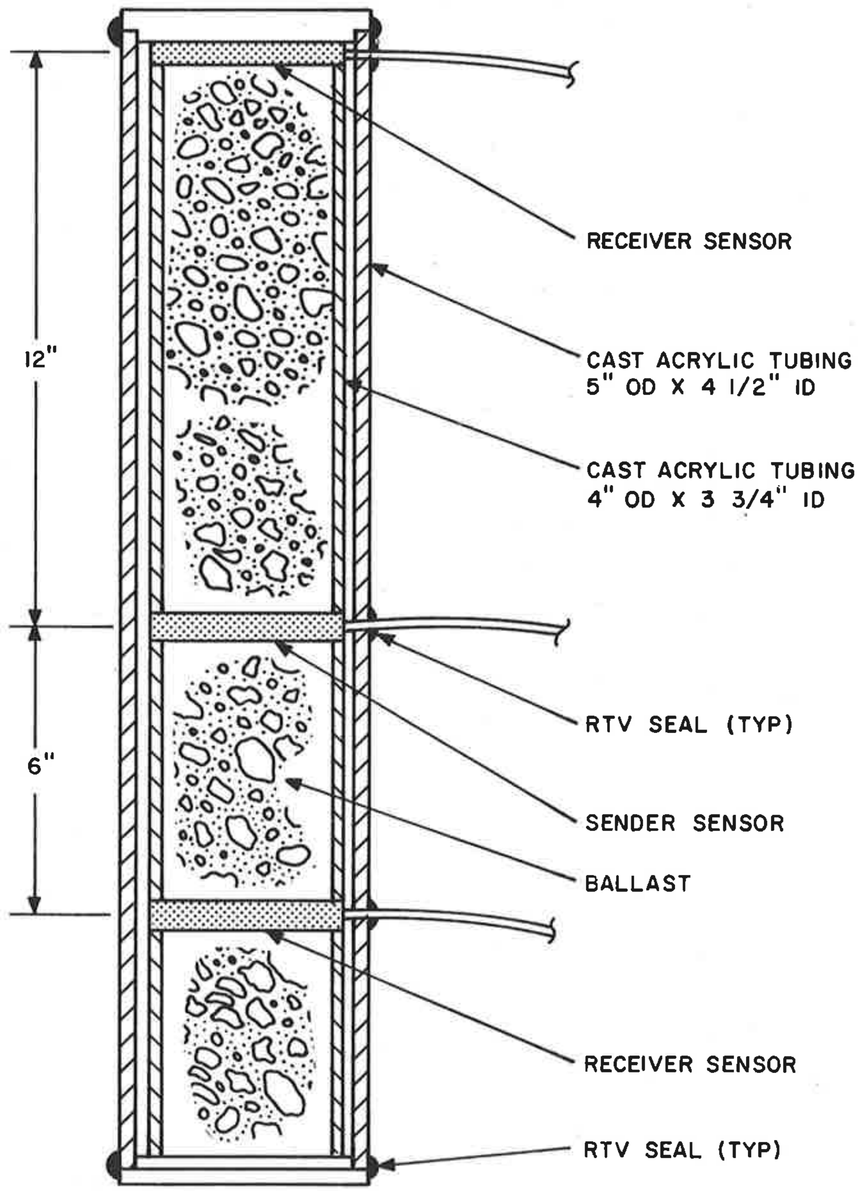


FIGURE 3.8. BISON FIELD COMPENSATOR CONFIGURATION

3.6.4. Instrumented Rail Clips

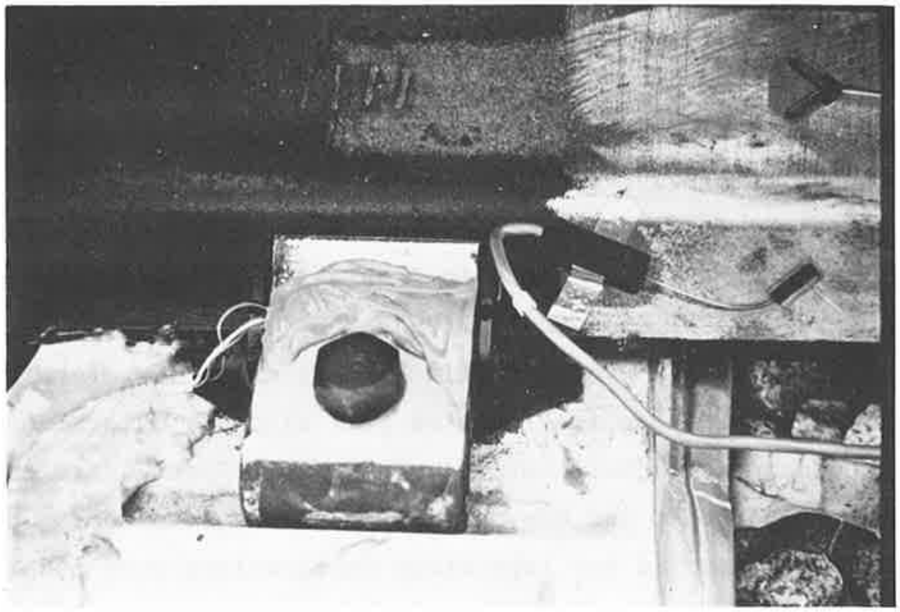
Eight Flexiclip rail fasteners, manufactured by The Rails Company, were obtained from TTC inventory and instrumented with full bridge strain gage circuits as shown in Figure 3.9. Strain gages employed were Micro-Measurements EA-13-250-BF-350 (1/4-inch gage length) for both active and inactive arms. Original plans called for laboratory load calibrations of these instrumented rail clips to determine the load versus sensitivity characteristics of each. Upon closer consideration, it was decided that the many variables in the interfacing components would render invalid any laboratory calibrations when reassembled in the field. In situ load calibration was therefore performed on the instrumented rail clips after installation in the TTT to determine the output sensitivities.

3.7 SITE INSTALLATION

The same types and quantities of transducers were installed at both the curved and tangent test areas of the Transit Test Track. As shown in Figures 3.10 and 3.11, the transducer orientation at the two test areas was identical except for being symmetrically opposite. The TTC O&M contractor, under the direction of KSC personnel, supplied much of the labor and equipment for the actual transducer installation. The following paragraphs describe in detail the installation processes. Since essentially the same procedures were employed for installations at both sites, this discussion will be based upon that at the curved test area with any differences noted. For orientation purposes, corresponding crosstie identification numbers at the tangent test area will be noted in parentheses.

3.7.1 Primary Transducer Arrays

The largest concentration of transducers was included within, between, and beneath crosstie numbers 428 -13 and -14 (365 +8 and +9) with a lesser number included beneath crosstie 428 -15 (365 +10). These transducer arrays are identified as #1, #2, and #3 Array on Figures 3.10 and 3.11 and the transducer orientations of each are shown in Figures 3.12, 3.13 and 3.14.



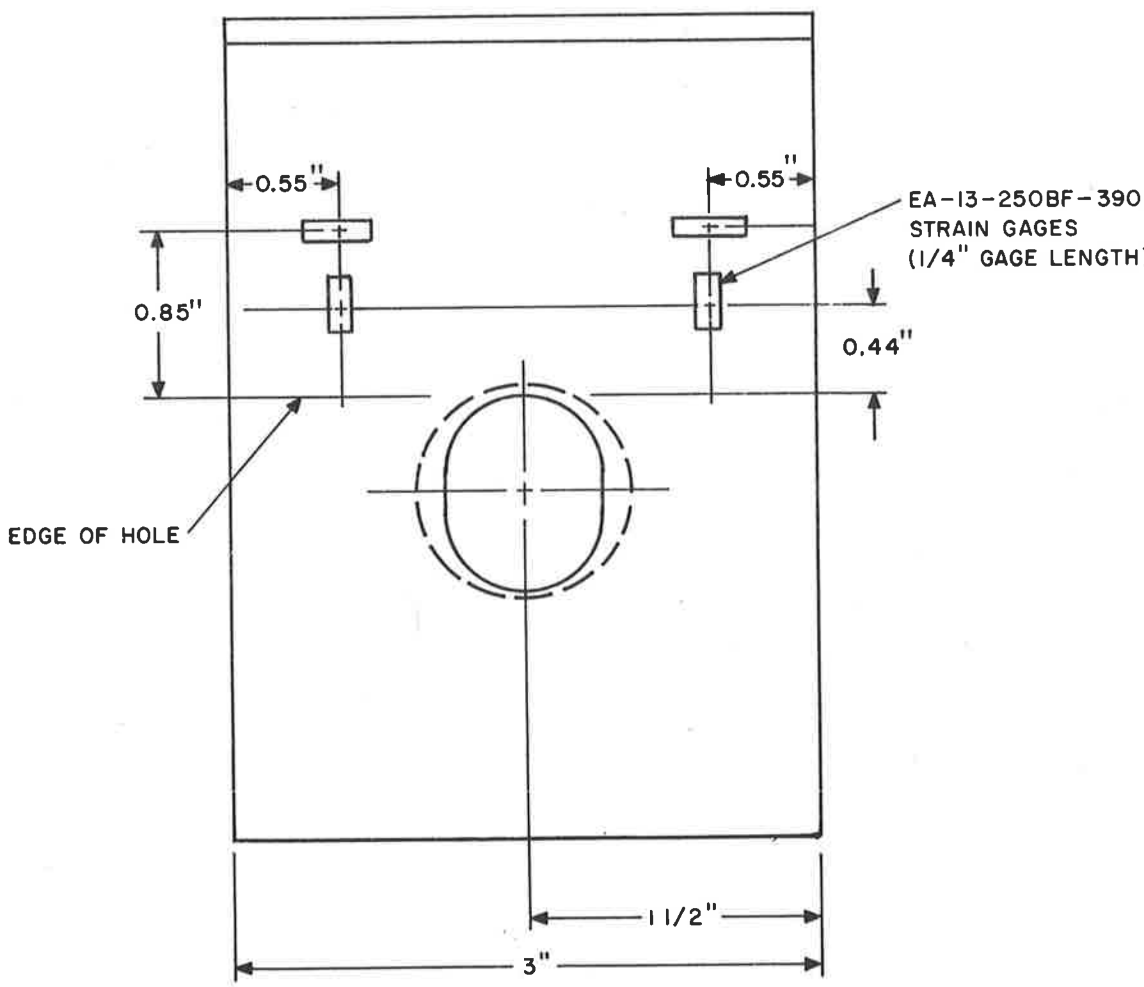


FIGURE 3.9. STRAIN GAGE INSTRUMENTATION OF RAIL CLIP

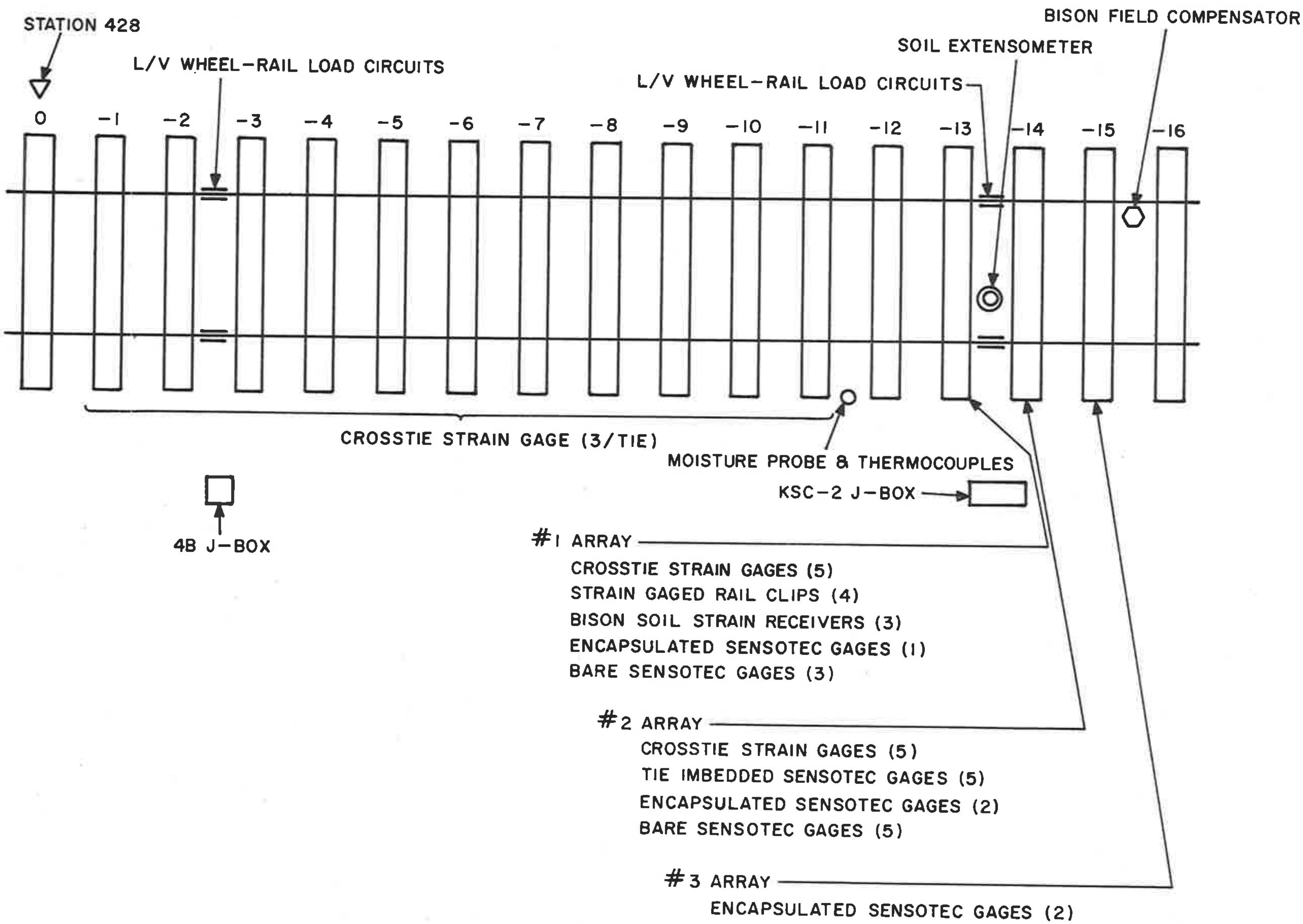


FIGURE 3.10. TRANSDUCER ORIENTATION AT CURVED TEST AREA

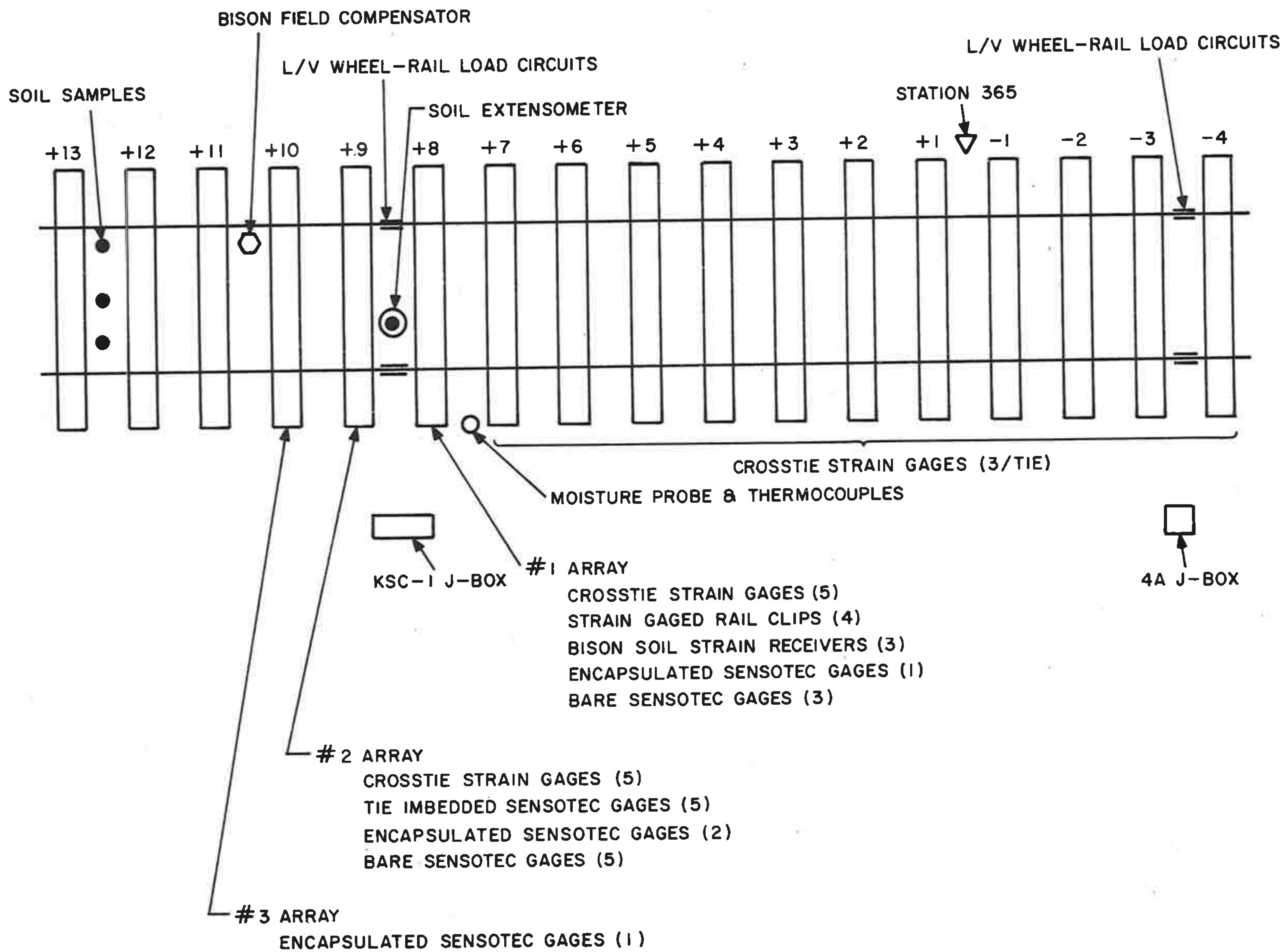


FIGURE 3.11. TRANSDUCER ORIENTATION AT TANGENT TEST AREA

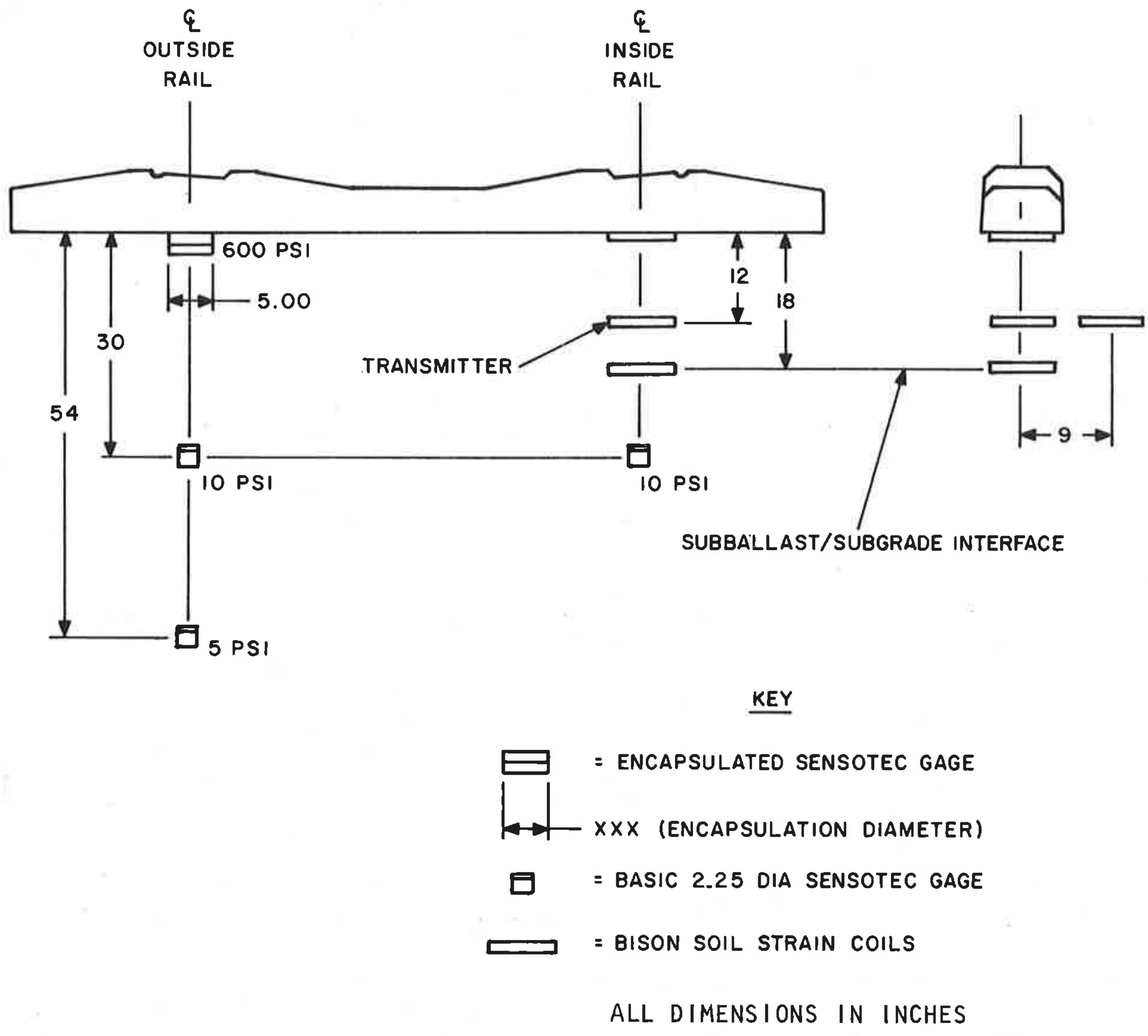


FIGURE 3.12. TRANSDUCER ORIENTATION - NO. 1 ARRAY (CURVED AND TANGENT TEST AREAS)

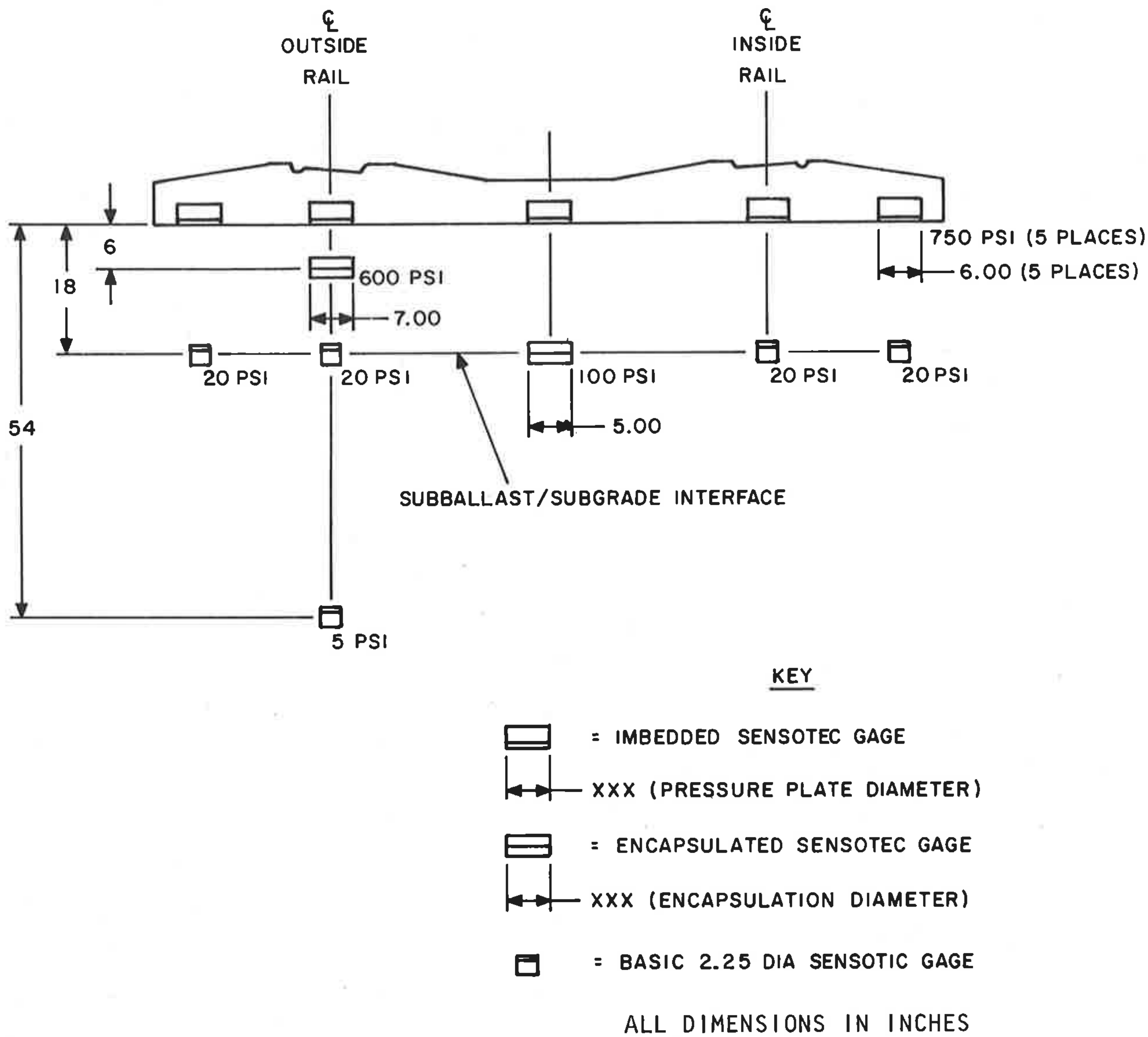


FIGURE 3.13. TRANSDUCER ORIENTATION - NO. 2 ARRAY
(CURVED AND TANGENT TEST AREAS)

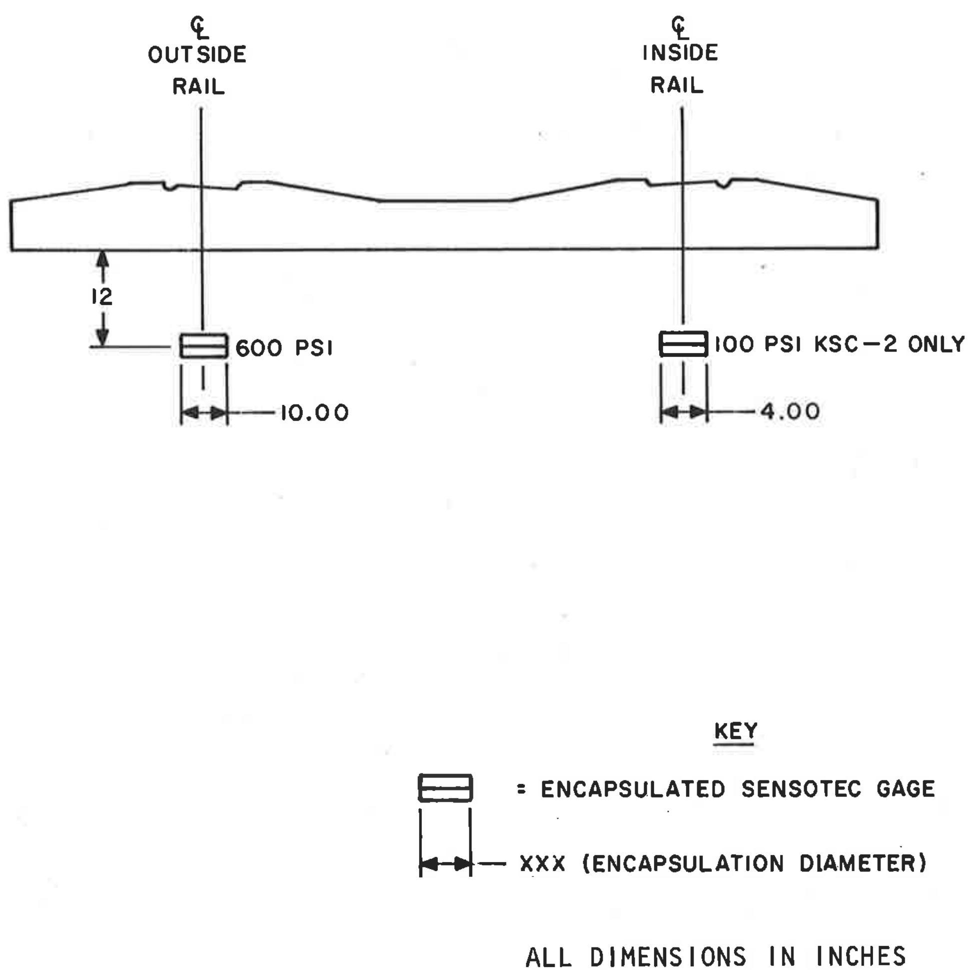


FIGURE 3.14. TRANSDUCER ORIENTATION - NO. 3 ARRAY
(CURVED AND TANGENT TEST AREAS)

To begin the transducer installation, ballast beneath crosstie numbers 428 -13 and -14 (365 +8 and +9) was scraped away, and these crossties were removed. Ballast was further removed to the subballast-subgrade interface. Using hand tools, the subgrade soil was trenched as shown in Figure 3.15 to provide for transducer implantation and lead wire routing.

Survey techniques were employed as shown in Figure 3.16 to insure transducer placement to within $\pm$1/4-inch of the desired position both vertically and laterally. At the curved test area, all instrumentation lead wires were routed through interconnected PVC piping, the termini of which were located immediately adjacent to each transducer. At the tangent test area, PVC piping was employed only within the ballast and subballast to protect instrumentation lead wires; those located below the ballast/subballast interface were routed directly through the sandy subgrade soil. This was done to minimize subgrade disturbances that resulted from additional trenching requirements solely for the PVC pipe that were observed at the curved test area. After each transducer was implaced, the respective holes were filled with subgrade soil which was hand-tamped to approximate the prevailing compaction as closely as possible without disturbing the transducer location or orientation.

After installation of the subgrade transducers in the #1 and #2 Arrays, the Terrametrics Model 1-RC single position borehole extensometer was installed in the hole provided. The integral 2-inch soil auger was screwed to the proper depth in the subgrade at the hole bottom using the setting tool provided. Attachment of the Carlson joint meter and upper portion of the extensometer were straight-forward and in accordance with the manufacturer's instructions.

Next, the previously instrumented and laboratory load calibrated crossties were inserted and secured in place to the rails with the Flexiclip rail fasteners at locations 428 -14 and -15 (365 +8 and +9) as shown in Figures 3.17 and 3.18. The strain gaged Flexiclip rail fasteners were employed to attach crosstie 428 -13 (365 +8).

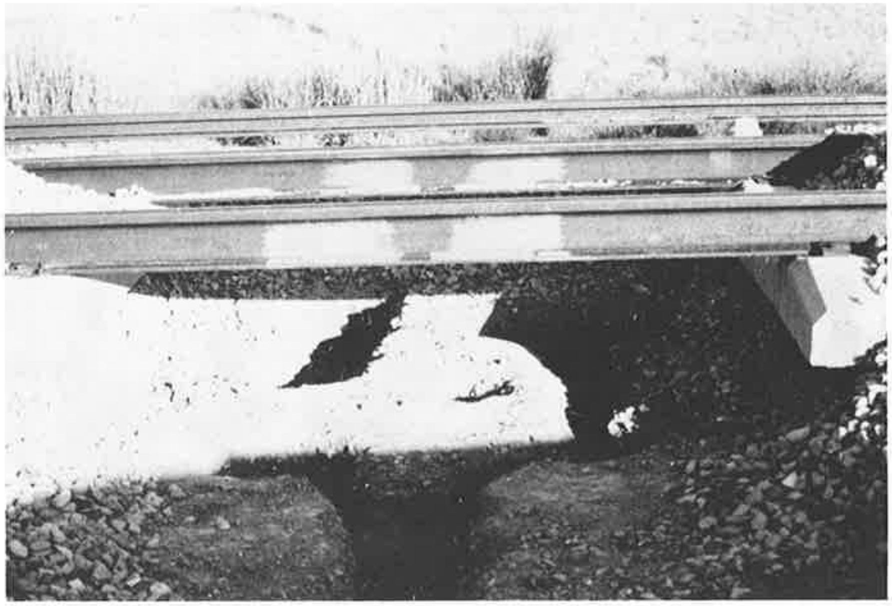


FIGURE 3.15. ROADBED TRENCHING PRIOR TO TRANSDUCER INSTALLATION

FIGURE 3.16. PLACEMENT OF TRANSDUCERS USING SURVEY TECHNIQUES

FIGURE 3.17. INSTALLATION OF INSTRUMENTED CROSSTIE

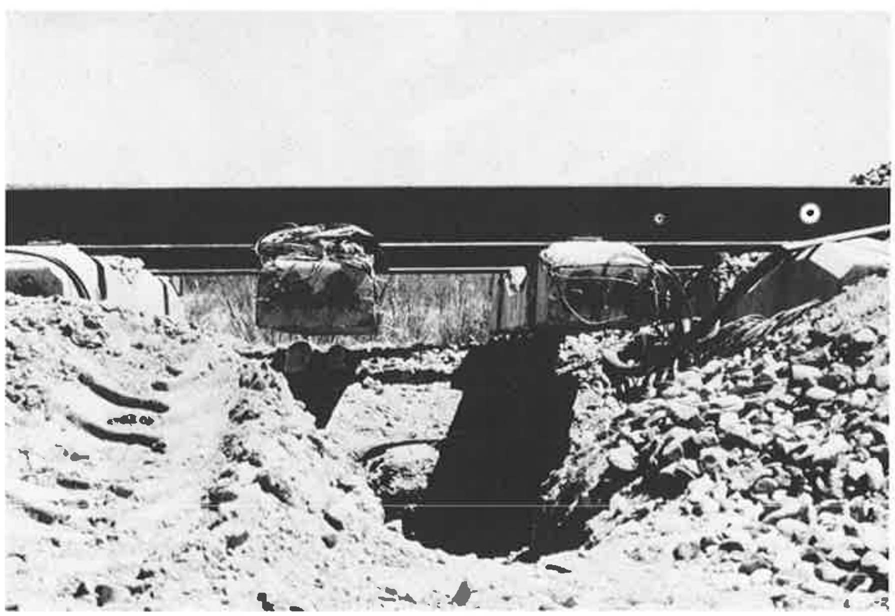


FIGURE 3.18. INSTRUMENTED CROSSTIES SECURED TO RAILS

The remainder of the subballast and ballast transducers in the #1, #2, and #3 Arrays were installed as the ballast was backfilled beneath the crossties and in the crib areas. One encapsulated Sensotic 0-100 psi soil pressure gage was found to be inoperative and therefore was not installed in the #3 array at the tangent test area. To consolidate the ballast in the excavated areas, a mechanical tamper was employed as shown in Figure 3.19. Close supervision was provided to guard against damage to the rail seat strain gages and disturbance of the ballast transducers.

3.7.2 Strain Gaged Crossties

As indicated in Figures 3.10 and 3.11, eleven crossties at each test area were instrumented with three strain gages each. These strain gages were installed by KSC personnel on the in situ crossties. Gage types, connections, and installation procedures matched those employed for the two instrumented and laboratory load calibrated crossties at each test area. The strain gage locating fixture was utilized to insure accurate and repeatable positioning of the rail seat and midspan strain gages identical to that of the calibrated crossties. Installation of the rail seat strain gages necessitated temporary removal of the crib ballast adjacent to each rail seat. Clamps were fabricated for use as shown in Figure 3.20 to apply the required bonding pressure. Formed stainless steel protective covers were bonded in place over each rail seat strain gage installation prior to backfilling of the ballast. Lead ingots were employed to apply vertical bonding pressure for the midspan strain gages. Formed stainless steel protective covers were also bonded in place over all midspan strain gage installations.

3.7.3 Miscellaneous Transducers

The Bison field compensator (Figure 3.21) was installed between crossties 428 +15 and -16 (365 +10 and +11) by removing the crib positioning the array at the proper elevation with the top receiver sensor located at the crosstie bottom plane, and backfilling the ballast.

FIGURE 3.19. BALLAST TAMPING OPERATIONS IN EXCAVATED AREA

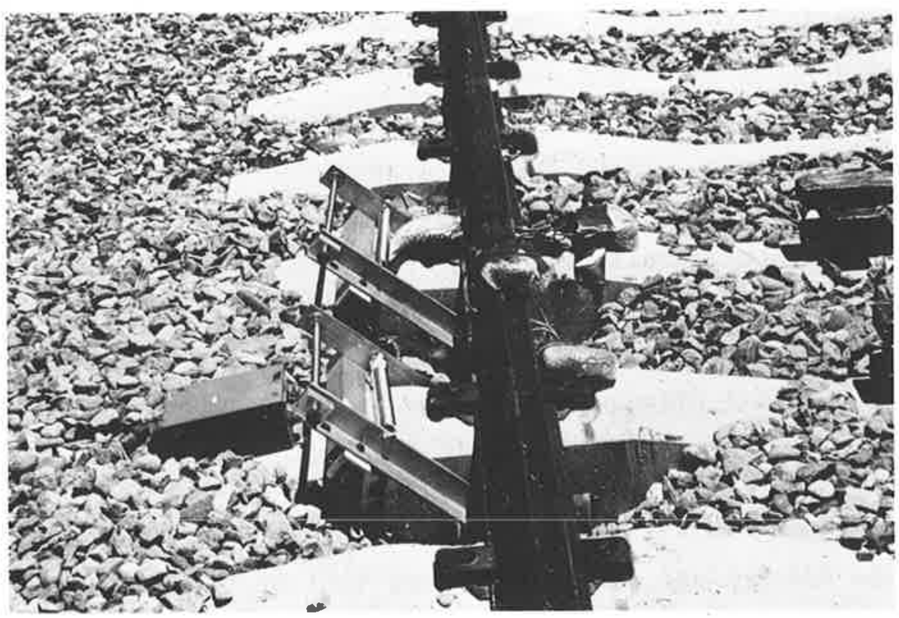


FIGURE 3.20. CLAMPS PROVIDE BONDING PRESSURE FOR RAIL SEAT STRAIN GAGES

FIGURE 3.21. BISON FIELD COMPENSATOR PRIOR TO INSTALLATION

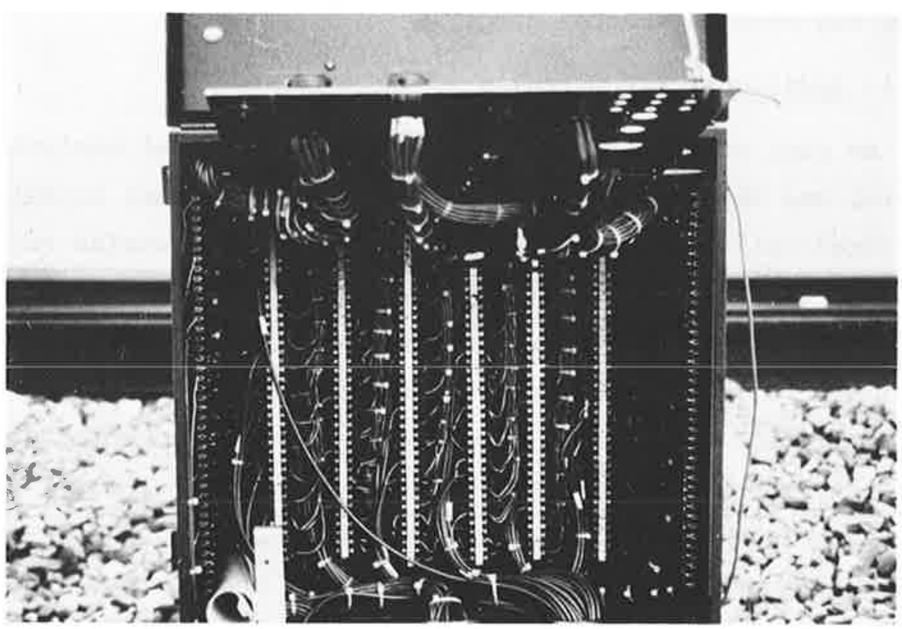


FIGURE 3.22. INTERNAL WIRING OF KSC J-BOX

All instrumentation lead wires were routed below ground to the respective KSC J-box at each test area where terminations were made to terminal strips as shown in Figure 3.22. The J-box hinged front connector panel provided the primary instrumentation interfaces to the TTC data van.

The TTC O&M contractor installed web and base chevron strain gage circuits on both rails between crossties 428 -2 and -3 (365 -3 and -4) and between crossties 428 -13 and -14 (365 +8 and +9) for measurement of lateral and vertical (L/V) wheel-rail loads. Strain gages employed were Hitec HBW-35-125-6-10GP (1/8 inch gage length) uniaxial gages welded to the rail base flange for lateral load measurement and Hitec HBWC-35-1256-10GP-TR (1/8-inch gage length) 90-degree chevron dual gages welded to the rail web at the neutral axis for vertical load measurement. Gage locations and circuit connections were as shown in Figure 3.23. Instrumentation lead wires for all L/V wheel-rail load circuits were routed along one of the two crossties immediately adjacent to bracket-mounted connectors located on the crosstie end.

The TTC O&M contractor also installed a vertical tube between crossties 428 -11 and -12 (365 +7 and +8) to accept the Soiltest NIC-5 nuclear moisture density meter. In the same area, the O&M contractor installed a vertical array of eight copper-constantan Type T thermocouples at depths of 0-, 12-, 18-, 24-, 30-, 36-, 42-, and 54-inches below the crosstie bottom plane.

3.7.4 Additional L/V Circuits

As part of the effort to determine statistical variations in lateral and vertical wheel-rail loads, KSC personnel installed ten L/V wheel-rail load measurement circuits on the outside rail of the TTT oval in the vicinity of the tangent test area as shown in Figure 3.24. Installation, connection and instrumentation lead wire routing were identical to those of the corresponding circuits installed by the TTC O&M contractor. The measurement locations were selected so that during a single passage of the NYCTA R-42 transit vehicle, every point on the circumference of each 34-inch diameter wheel would be encompassed by at least one of the 10-inch measurement zones. The location of the

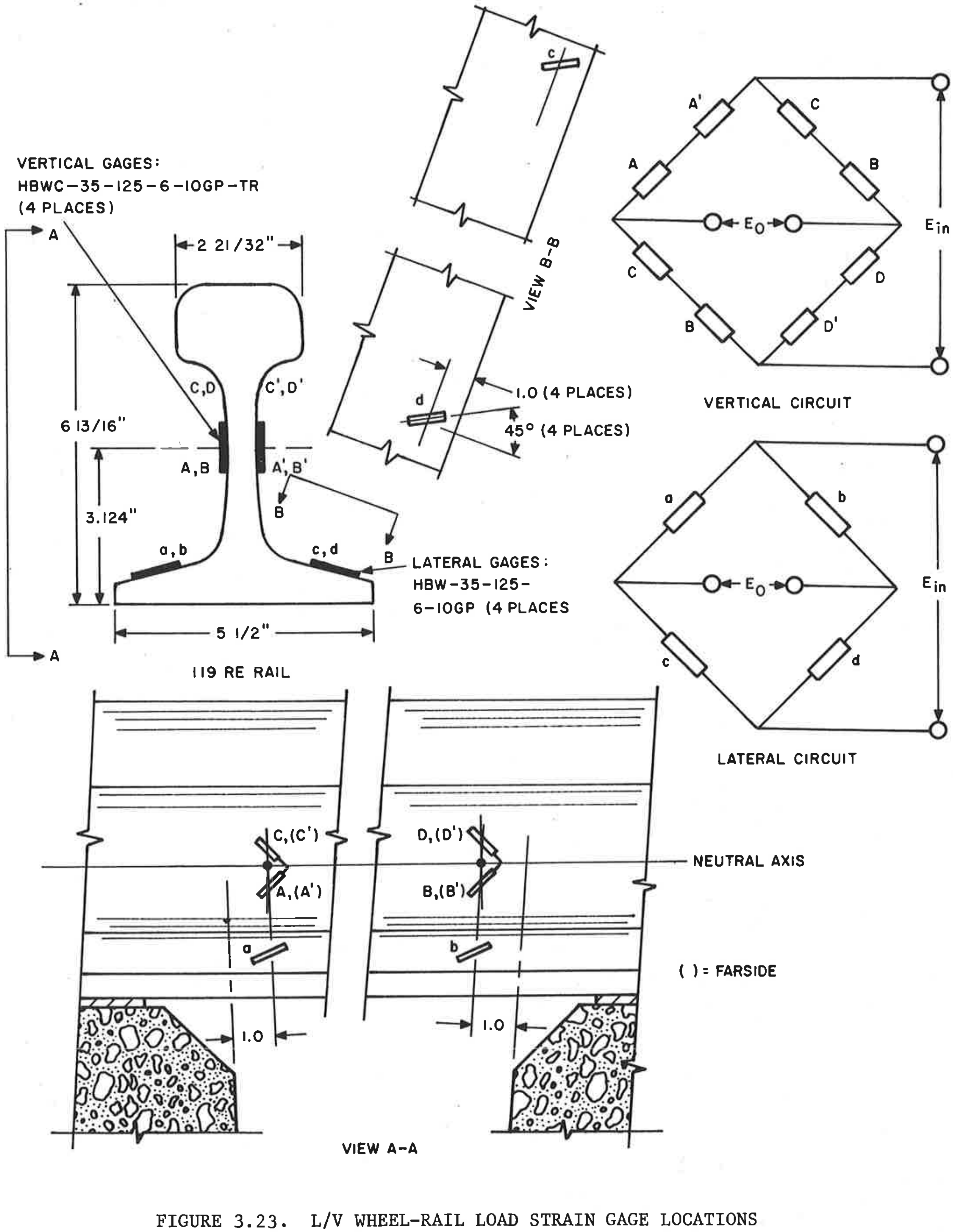
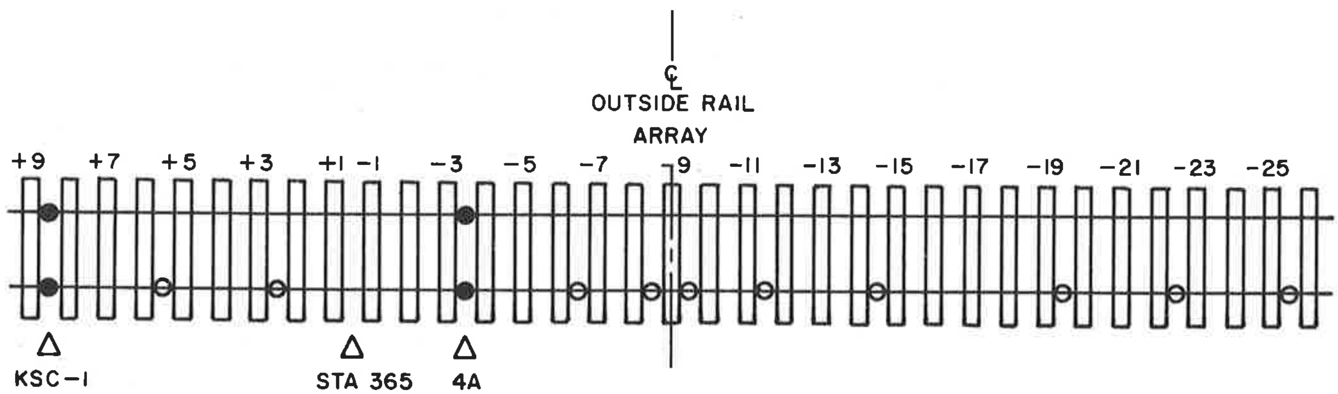


FIGURE 3.23. L/V WHEEL-RAIL LOAD STRAIN GAGE LOCATIONS AND CIRCUIT CONNECTION



● L/V WHEEL-RAIL LOAD CIRCUITS INSTALLED BY TTC O&M CONTRACTOR

○ L/V WHEEL-RAIL LOAD CIRCUITS INSTALLED BY KSC

FIGURE 3.24. L/V WHEEL-RAIL LOAD MEASUREMENT CIRCUITS IN TANGENT TEST AREA

overall array was chosen to accommodate future efforts to measure wheel-rail loads induced by lateral and/or vertical track perturbations; perturbation lengths of up to 80-feet, symmetrical about crosstie 365 -9, can be incorporated without disturbing the instrumentation arrays at KSC-1.

3.8 SITE DATA ACQUISITION AND RECORDING

The TTC O&M contractor was responsible for integration, operation, and maintenance of all test-related equipment including the transit vehicles, the TTC No. 54 Calibration Car, the TTC No. 408 Data Van and ancillary items such as the diesel power supply and specialized transducer/instrumentation items. KSC personnel assisted in the set-up and data acquisition effort wherever appropriate.

The block diagram for data acquisition and recording using the TTC No. 408 Data Van is given in Figure 3.25. All data except for soil temperature and moisture density were FM multiplexed and recorded on analog tape. Resistive calibration techniques were employed for most transducers to obtain the comparative signal strengths for scaling of the output data.

3.9 PRE TEST CALIBRATIONS

A series of load calibration tests was performed on each L/V wheel-rail load measurement circuit to determine load versus output characteristics of both the lateral and vertical circuits and the influence of vertical load on lateral circuit sensitivity. Load calibration testing was also performed on the strain gaged Flexiclip rail fasteners to determine the load sensitivities. The L/V circuits installed by the TTC O&M contractor and KSC and the strain gaged rail fasteners were load calibrated in accordance with the test plan set forth in Appendix C, Calibration Loading Test Plan for L/V rail circuits and Instrumented Crossties.

All calibration loading was applied using the TTC No. 54 Calibration Car, a loaded 100-ton bottom-dump hopper car incorporating a hydraulic loading apparatus mounted between the hopper chutes. This apparatus has

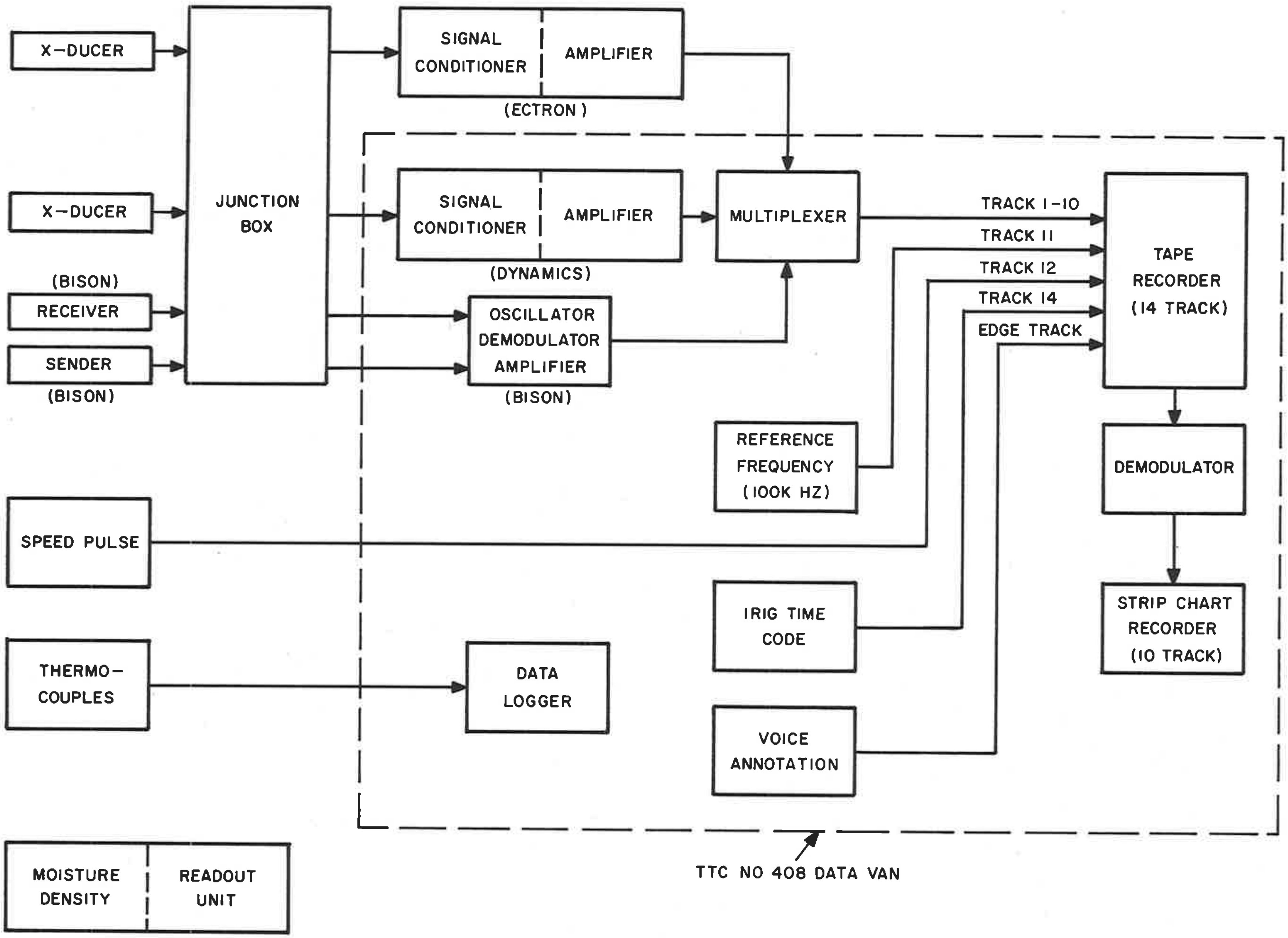


FIGURE 3.25. DATA ACQUISITION AND RECORDING SYSTEM BLOCK DIAGRAM

the capability of applying simultaneous loads of up to 40,000 pounds vertically and 20,000 pounds laterally to both rails. Loading is transmitted to each rail through a section removed from a "partially worn" wheel. Load cells in series with the vertical and lateral hydraulic cylinders monitor the applied load. Details of the loading apparatus are shown in Figures 3.26 and 3.27.

The TTC O&M contractor operated the calibration car and provided data acquisition, recording and plotting. For the strain gaged rail clips, plots were obtained showing output sensitivity versus vertical load to 20,000 pounds. For each L/V wheel-rail load measurement circuit, a calibration plot was obtained for the loading sequences given in Appendix C.

3.10 TRANSIT VEHICLE TEST OPERATIONS

Two types of transit vehicles, each type operating as married pairs, were employed to induce forces in the transit track structure. The NYCTA R-42 transit vehicles on loan to the TTC, were used in both the crush loaded and light configuration for data acquisition passes at both the curved and tangent test areas. In addition, the MBTA Blue Line transit vehicles, then undergoing testing at the TTC, were similarly employed in the crush loaded configuration only, for data acquisition passes at both test areas. Finally, the crush loaded R42 transit vehicles were again used for data acquisition passes at the tangent test area, this time to allow measurement and recording of wheel-rail loads from the fourteen L/V wheel-rail load measurement circuits installed in this area shown in Figure 3.24.

As shown in Table 3.1, a total of sixty-eight transit vehicle data passes was made between September 19 and December 10, 1979, during which data was recorded from the stations indicated. This seemingly large number of data passes was necessitated in part by the data acquisition and recording limitations of the TTC No. 408 data van and ancillary equipment. Repeated data acquisition passes at the curved and tangent test areas were required in an attempt to obtain data from transducers either excluded previously or that had produced data of doubtful quality.

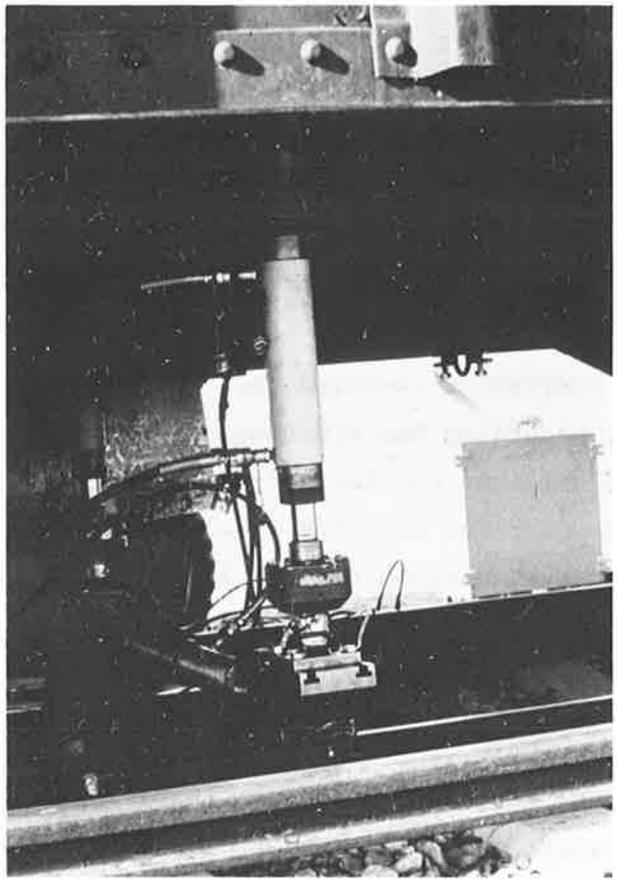


FIGURE 3.26. VERTICAL LOADING STRUT ON TTC CALIBRATION LOADING CAR

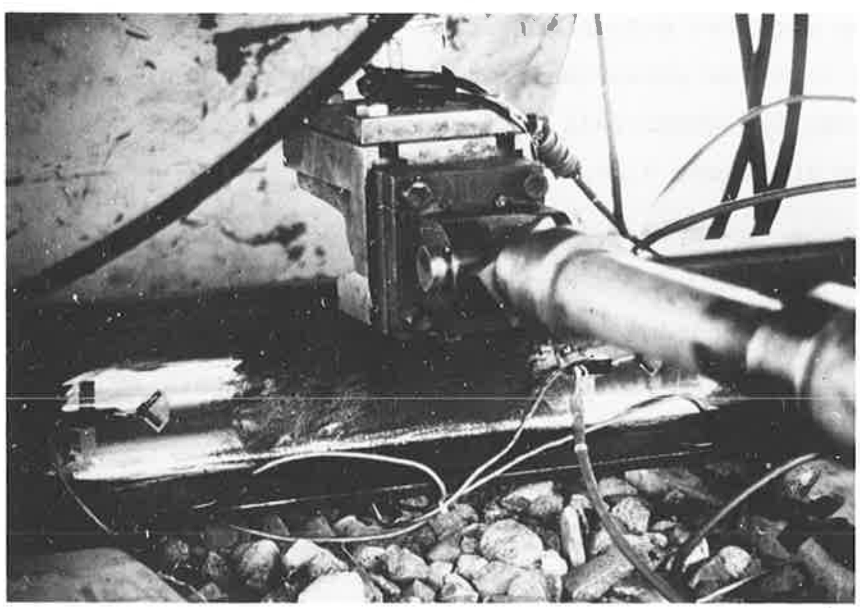


FIGURE 3.27. LATERAL LOADING STRUT ON TTC CALIBRATION LOADING CAR